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IN-PLANE STRESS WAVES FOR NDE OF GRAPHITE FIBER/EPOXY COMPOSITES

ROY F. PELLERIN
MATERIALS TESTING & EVALUATION BRANCH

April 1988

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ABSTRACT

Due to the complexity of the physical structure of composites, NDE techniques which evaluate structural properties are required rather than the mere detection of inclusions, voids or discontinuities. This paper describes NDE techniques that have been used for evaluation of properties in wood, a natural composite, and the results of utilizing longitudinal stress waves for evaluation of graphite fiber/epoxy composites.

The objectives of this study were: 1) to become familiar with graphite fiber/epoxy composites; and 2) to establish if the NDE stress wave method, for wood, is appropriate for evaluation of the properties of composites, such as, graphite fiber/epoxy.

One of the conclusions of this study was that graphite fiber/epoxy composites respond to stress wave analysis similar to the natural composite, wood. More specifically, the stress wave method of nondestructive evaluation of graphite fiber/epoxy composites can be used to accurately assess the strength and moduli properties within panels.

Another conclusion was that the results of this study gave strong indication that every piece evaluation is both possible and feasible for quality control and process control purposes.

FOREWORD

This program was conducted at the Nondestructive Evaluation Branch, U.S. Army Materials Technology Laboratory, Watertown, MA under the Army Summer Faculty Research and Engineering Program. MTL personnel who contributed to this program include Dr. A. L. Broz, R. H. Brockelman and H. P. Hatch.

CONTENTS

INTRODUCTION

With the expressed interest by the Department of Defense, for use of fiber-reinforced composites, the need for nondestructive evaluation (NDE) to assure structural integrity is apparent. The application of established NDE techniques for isotropic, homogeneous materials, such as metals, are of limited value for evaluation of fiber-reinforced composites. Also, because of the complexity of the physical structure and the inherent variability of composites, evaluation of coupon-type specimens is not adequate.

Due to the complexity of the physical structure of composites, NDE techniques which evaluate structural properties, rather than the mere presence of inclusions, voids, or discontinuities, are required.

Vibrational techniques for NDE of wood, a natural composite, have been developed at Washington State University. One method, longitudinal stress waves, is described in more detail in this document. Also described in this document are various studies on NDE of wood.

The primary goal for NDE of wood is to make wood an "engineering material." In order to accomplish this, the evaluation of structural properties for each full-sized component is required.

In the production of wood products, such as particle board, NDE methods are utilized for process control. Similarly, NDE methods should provide valuable process control in the production of fiber-reinforced composites.

OBJECTIVES

The objectives of this study are: (1) to become familiar with graphite fiber/epoxy composites; and (2) to establish if the NDE stress wave method, for wood, is appropriate for evaluation of the properties of composites such as graphite fiber/epoxy.

BACKGROUND INFORMATION FOR NONDESTRUCTIVE EVALUATION OF WOOD

Transverse Vibrations

Nondestructive evaluation of wood is used to predict the elastic and strength properties without altering "end-use" capabilities. Vibration analysis provides a dynamic means of nondestructively evaluating wood. Since the eighteenth century, a relationship has been known to exist between the vibrational and elastic properties of wood.[1] In recent years, an increasing interest has developed in the relationship between the vibrational and mechanical properties of wood.

Low-stress vibration permits the measurement of two fundamental properties of a material: energy storage and energy dissipation. In the absence of rapid energy loss, the natural frequency of vibration of an object serves as an indication of

1. PELLERIN, R. F. *A Vibrational Approach to Nondestructive Testing of Structural Lumber.* Forest Products Journal 15(4), 1965, p. 93-101.

energy storage. In contrast, the logarithmic decay of an oscillating body serves as an indication of energy dissipation. Dr. Ben Jayne[2] hypothesized that the energy storage and energy dissipation factors from natural vibration were related to the same mechanisms that control the mechanical properties of a material. In his hypothesis, modulus of elasticity (MOE) was represented by energy storage, and modulus of rupture (MOR) was represented by energy dissipation.

Several researchers[1-3] have successfully demonstrated a relationship in wood between static MOE and dynamic modulus of elasticity (E_d). These researchers used transverse vibration to measure E_d in wood ranging from small clear specimens to structural lumber.

The relationship between energy dissipation and ultimate strength, however, has not been as evident. In analyzing small straight grained specimens of Sitka spruce with transverse vibration, Jayne[2] showed that only a slight relationship existed between logarithmic decrement and modulus of rupture. More useful correlations were achieved when a combination of logarithmic decrement and E_d was used to predict MOR. Pellerin[1] reported similar results when working with construction lumber of various moisture contents, sizes, and grades. Using the ratio of E_d over logarithmic decrement to predict MOR, correlation coefficients as high as $r = 0.92$ were reported.

Stress Waves

Stress wave propagation, like transverse vibration, is a dynamic process. Longitudinal stress wave propagation differs from transverse vibration in two distinct ways. First, the direction of excitation is along the longitudinal axis of the material. Second, the frequency of excitation is approximately 1000 times greater. Despite these differences, longitudinal stress wave analysis, and transverse vibration analysis provide comparable measurements of the dynamic modulus of wood.

Galligan and Courteau[4] demonstrated this close correspondence by using longitudinal stress wave analysis and transverse vibration analysis to predict the static flexural moduli of 40 Douglas fir 2 x 6's. A linear regression analysis comparing the dynamic moduli measured by stress wave analysis to the dynamic moduli measured by transverse vibration analysis, resulted in a correlation coefficient of 0.966. The researchers also reported that longitudinal stress wave analysis was faster to use than transverse vibration, and that the system was not encumbered by support and specimen configuration problems.

The propagation of longitudinal stress waves in a material is influenced in a complex manner by the material's mechanical and physical properties. In order to be used for practical application, the equations describing stress wave propagation have been simplified to elementary one-dimensional wave equations, as applied to isotropic, homogeneous materials. For a prismatic bar, whose lateral dimensions are relatively small compared to the wavelength of the propagating wave, the resulting equation describing wave velocity is:

2. JAYNE, B. A. *Vibrational Properties of Wood as Indicies of Quality.* Forest Products Journal 9(11), 1959, p. 413-416.
3. JAMES, W. L. *Vibration, Static Strength, and Elastic Properties of Clear Douglas-Fir at Various Levels of Mositure Content.* Forest Products Journal 14(9), 1964, p. 409-413.
4. GALLIGAN, W. L. and COURTEAU, R. W. *Measurement of Elasticity of Lumber with Longitudinal Stress Waves and the Piezoelectric Effect of Wood.* Proceedings, Second Symposium on Nondestructive Testing of Wood, Washington State University, Pullman, WA, 1965, p. 223-244.

$$C = (E/\rho)^{1/2} \quad (1)$$

where C is the wave speed, E is the dynamic modulus of elasticity, and ρ is the mass density of the bar. Although wood is neither isotropic nor homogeneous, use of this equation with wood yields E_d values that agree closely with corresponding static moduli.

Several researchers have used longitudinal stress wave analysis to predict the elastic and strength properties of various wood products. Koch and Woodson[5] used longitudinal stress waves to measure E_d of 1/6-inch-thick southern pine veneer strips. The strips were used to construct laminated beams. By placing the highest E_d values at the outer portions of the beam, and the lowest E_d values at the center, the researchers were able to increase the allowable bending stress an average of 30% over that of conventionally manufactured beams. Kunesh[6] reported excellent results when using longitudinal stress waves to assess the stiffness properties of veneer and parallel laminated veneer products. His results indicated that veneer sheet quality, as measured using stress waves, translated directly into product strength properties with low variability.

Pellerin and Galligan[7] tested green Douglas fir logs with longitudinal stress waves and ranked each log according to the dynamic modulus of elasticity. The logs were then cut into structural lumber and each board was stress waved and destructively tested. The researchers found that, based on average mechanical properties, ranking the logs by stress wave analysis successfully predicted the relative quality of the lumber in the logs.

Pellerin and Morschauser[8] used stress wave propagation time as a predictor of MOE and MOR of 221 particle board panels produced in four different plants. Correlation coefficients of 0.93 and 0.87 were achieved using the reciprocal of stress wave propagation time squared to predict panel MOE and MOR, respectively. These coefficients increased to 0.95 and 0.93 when the analysis was rerun for an individual plant. From these results, the researchers concluded that stress wave analysis could be used as an efficient grading and sorting tool.

As a separate investigation, Pellerin and Morschauser[8] found that stress wave analysis could be used at elevated temperature conditions to accurately predict the elastic and flexural properties of particle board at ambient conditions. From this, they concluded that stress wave analysis could be used as a continuous quality control device, installed directly in the production line. For information, typical properties for solids are shown in Table 1.

It is interesting to note that the velocity of propagation of stress waves in wood parallel to grain is equivalent to that in steel and aluminum.

5. KOCH, P. and WOODSON, G. E. *Laminating Butt Jointed, Log-Run Southern Pine Veneers Into Long Beams of Uniform High Strength.* Forest Products Journal 18(10), 1968, p. 45-51.
6. KUNESH, R. H. *Using Ultrasonic Energy to Grade Veneer.* Proceedings, Fourth Symposium on Nondestructive Testing of Wood, Washington State University, Pullman, WA, 1978, p. 275-278.
7. PELLERIN, R. F. and GALLIGAN, W. L. *Nondestructive Method of Grading Wood Materials.* British Patent No. 1244699.
8. PELLERIN, R. F. and MORSCHAUSER, C. R. *Nondestructive Testing of Particle Board.* Proceedings, Seventh International Particle Board Symposium, T. M. Maloney, ed., Washington State University, Pullman, WA, 1973, p. 251-260.

Attenuation of Stress Waves

Longitudinal stress waves, travelling in an inelastic material such as wood, attenuate at a rate which is related to the energy dissipation factors of the material. Recall, that Jayne[2] suggested that these energy dissipation factors were directly related to the mechanisms that control the strength of wood. By themselves, the energy dissipation factors, as measured by attenuation, have not been good predictors of the ultimate strength of wood. However, when combined with energy storage factors, such as modulus of elasticity of stress wave velocity, useful correlations have been reported.

Kaiserlik[9] incorporated particle velocity attenuation with stress wave propagation velocity and board density to predict the ultimate tensile strength (UTS) of 21 Douglas fir 2 x 4's. Using E_d as a predictor of UTS, he reported a correlation coefficient of 0.835. By combining attenuation, wave velocity, and specific gravity, this coefficient improved to 0.905.

Ross[10] and Vogt[11] used particle velocity attenuation, stress wave velocity, and panel specific gravity to predict the tensile and flexural properties of a wide variety of wood-based particle composite panels. Using a multi-variable linear regression model of these parameters, they were able to account for 90% of the variations in ultimate tensile strength, and 94% of the variation in ultimate bending strength for the material tested.

This literature review illustrates the usefulness of nondestructive evaluation in predicting the elastic and strength properties of a wide variety of wood products.

Elementary Stress Wave Theory

The equations describing the propagation of longitudinal stress waves in composite materials are very complex. The complexity can be reduced by assuming the material behaves as if it were elastic, isotropic, and homogeneous. By restricting the deformations, caused by the propagating stress waves, to a single axis of the material, the differential equations are reduced to simple wave equations. If the longitudinal stress wave is assumed to be of plane geometry, exact solutions to the equations are possible.

When a material is stressed with a suddenly applied load, the resulting deformations and stresses are not immediately transmitted to all parts of the body. Consider a long, prismatic bar of elastic material, subjected at its end to a uniformly distributed compressive force for a short period of time. As a result of this force, a compressed zone of moving particles is formed (Figure 1). This zone, propagates down the bar with the leading edge passing over and exciting new particles. At the same time, particles near the back of the zone are passed over, and return to rest. The particles within the zone travel only short distances, whereas the zone propagates back and forth over the length of the bar. The zone, or wave, travels at a constant velocity, which is dependent upon the material properties through which it propagates.

9. KAISERLIK, J. H. *Attenuation of Stress Waves as an Indicator of Lumber Strength.* Masters Thesis, Washington State University, Pullman, WA, 1975.
10. ROSS, R. J. *Stress Wave Speed and Attenuation as Predictors of the Tensile and Flexural Properties of Wood-Based Particle Composites.* Ph.D. Dissertation, Washington State University, Pullman, WA, 1984.
11. VOGT, J. J. *Evaluation of the Tensile and Flexural Properties and Internal Bond of Medium Density Fiberboard Using Stress Wave Speed and Attenuation.* Masters Thesis, Washington State University, Pullman, WA, 1985.

When the compression wave reaches the end of the bar, it is reflected back in the opposite direction as a tension wave. Since the particles in the wave are now in tension, the particles in the bar continue to displace in the original direction despite the change in wave direction. Therefore, particle displacement in compression waves is in the same direction as wave displacement, whereas in tensile waves, particle displacement is in the opposite direction of wave displacement.

Bertholf[12] derived two separate equations relating particle velocity to wave velocity. The first was derived by analyzing the deformation in a bar caused by a given stress. The equation can be written as

$$v = \frac{\sigma C}{E} \tag{2}$$

where v is the particle velocity, σ is the stress, C is the wave velocity, and E is the modulus of elasticity.

The second equation was derived by setting the change in momentum of the propagating wave equal to the impulse of the initiating force. The equation can be written as

$$v = \frac{\sigma}{\rho C} \tag{3}$$

where v is the particle velocity, σ is the stress, C is the wave velocity, and ρ is the mass density of the bar. Combining Equations 2 and 3 results in the equation describing wave propagation velocity (Equation 1).

Equations of Motion

The one-dimensional wave equation describes the motion of a section of bar subjected to longitudinal stress waves. The wave equation can be derived by summing the forces in a differential element of the bar (Figure 2). For an elastic material the one-dimensional wave equation can be written as:

$$C^2 \frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2} \tag{4}$$

where C is the wave velocity and u is the longitudinal displacement of the cross section of the bar at a location (x).

Internal friction mechanisms prevent composites from behaving like a true elastic material. As a result of these mechanisms, the elastic energy produced during vibration is dissipated in the form of heat energy. While the internal friction mechanisms have no effect on the velocity of the propagating wave, they attenuate the motion of the individual particles, causing all particles to eventually come to rest.

The wave equation describing motion of a cross section of a bar in such a viscoelastic material is a bit more complex than that for an elastic material.

12. BERTHOLF, L. D. *Use of Elementary Stress Wave Theory For Prediction of Dynamic Strain in Wood.* Washington State Institute of Technology, Bulletin 291, Washington State University, Pullman, WA, 1965.

The equation includes an additional term which accounts for the effect of internal friction in the material[13]. The equation can be written as:

$$C^2 \frac{\partial^2 u}{\partial x^2} + D/\rho \frac{\partial^3 u}{\partial^2 x \partial t} = \frac{\partial^2 u}{\partial t^2} \tag{5}$$

where D is the term describing the internal dampening capacity. Ross[10] derived the general solution for this equation which reveals that particle motion diminishes at a rate that is a function of the internal dampening characteristics of the material. The general solution may be written in the form:

$$u\ (x,\ t) = e^{-\alpha t}\ [f_1\ (x + ct) + f_2\ (x - ct)] \tag{6}$$

where u is the function of the internal dampening mechanisms of the material and f_1 and f_2 are functions describing two waves travelling at the same velocity but in opposite directions. This analysis indicates that by monitoring particle velocity at any cross section of a longitudinally vibrating viscoelastic bar, the period between pulses will remain unchanged, but the amplitude of each pulse will diminish exponentially with time.

PROCEDURE

The initial week of this study was used to become acquainted with MTL personnel and facilities. In return, a seminar entitled, "Nondestructive Evaluation of Wood Products for Quality Assurance and Process Control," was presented.

The next two weeks were utilized by performing evaluations of several types of fiber-reinforced composites. The equipment used was that possessed by MTL and a Metriguard Model 239A Stress Wave Timer that was brought from Washington State University. The specifications for the stress wave timer is reported in the Appendix of this document.

The results of these preliminary investigations showed that there was a good corresponden : of the evaluations done by the various methods. A primary difference in the methods does exist in that the MTL equipment is designed to detect the presence of voids, inclusions, or discontinuities in the material; whereas, the stress wave timer is designed to evaluate the influence of material variables on the mechanical properties of that material.

The stress wave timer was used to measure the modulus of elasticity values of many materials including steel, aluminum, wood, plexiglass, and several composites. Stress wave times were also used to measure the fiber orientation in sheets of paper and the influence of moisture on properties of paper.

13. SETO, W. W. *Mechanical Vibrations.* McGraw-Hill Book Company, New York, NY, 1964.

Based on these findings, a study was designed to assess the value of the stress wave timer for evaluation of graphite fiber/epoxy composites. Six 18-inch by 18-inch graphite fiber/epoxy panels were selected for this study. Two of the panels were 7-ply unidirectional lay-ups, two were 24-ply unidirectional lay-ups, and two were 16-ply ± 45-degree lay-ups.

The panels were first nondestructively evaluated by measuring stress wave times within the plane of the panels along rays spaced 15 degrees apart as shown in Figure 3.

During the process of measuring the stress wave times, it was noted that the stress wave was highly attenuated along certain rays. Therefore, a Nicolet Digital Oscilloscope was utilized to measure this attenuation.

A second set of stress wave times were measured on 2-inch increments along the edges of the panels as shown in Figure 4.

Upon completion of the stress wave evaluation, the panels were C-scanned with MTL equipment. Due to the physical limitations of the equipment, an 11-inch by 11-inch area in the center of each panel was evaluated. Due to the exposure, by both the stress wave and C-scan methods, of an apparent defect in Panel no. 4, a 16-ply ± 45-degree lay-up, the panel was X-rayed.

After all the nondestructive evaluations were accomplished, the panels were prepared for cutting into specimens for physical testing. The panels were marked so that 1/2-inch-wide specimens could be cut along the rays that the stress wave times were measured. This made a total of 24 specimens per panel.

After cutting, each specimen was weighed and measured for width, thickness, and length. Then stress wave times were again measured over the center six-inches of each specimen.

Each specimen was then physically loaded in bending, within the elastic limit, to establish modulus of elasticity values in bending and ultimately stressed to failure in tension to establish the ultimate tensile stress and modulus of elasticity in tension.

Upon completion of all nondestructive evaluation and destructive testing, the data were analyzed by regression analyses.

RESULTS AND DISCUSSION

The data and test results for each of the specimens cut from Panels 1 through 6 are tabulated in Tables 2 through 7, respectively.

Tables 8 through 15 report the regression equation, coefficient of determination and correlation coefficients of each panel for flexural MOE versus dynamic MOE and reciprocal of stress wave time squared, tensile MOE versus dynamic MOE and reciprocal of stress wave time squared, and ultimate tensile stress versus dynamic MOE and reciprocal of stress wave time squared, respectively.

Figures 5 through 33 show the individual plots of the regression lines reported in Tables 8 through 15. As indicated by the magnitude of the coefficients of determination, the individual points fall very close to the regression lines for the various analyses.

Figures 34 through 38 are plots of the ultrasonic scanning that was done prior to stress wave evaluation on Panels 1 through 6, respectively. There seems to be no relationship between the C-scans and the properties within the panels.

Panel 3, a 24-ply unidirectional lay-up, and Panel 4, a 16-ply ± 45-degree lay-up, were used in Figures 39 through 48 to show the distribution of various properties within the panels. These figures show that the properties of the panels are very dependent on the orientation of the graphite fibers within the panel, as they should.

CONCLUSIONS

One of the conclusions of this study was that graphite reinforced composites respond to stress wave analysis similarily as the natural composite, wood. More specifically, the stress wave method of nondestructive evaluation of graphite-reinforced composites can be used to accurately assess the strength and moduli properties within the panels.

Another conclusion was that the results of this study gave strong indications that every piece evaluation is both possible and feasible for quality control and process control purposes.

RECOMMENDATIONS

It is recommended that studies of the stress wave method be conducted with specific end-uses of the composite in mind. It is also recommended that studies of the implementation of stress waves for quality control and process control be conducted.

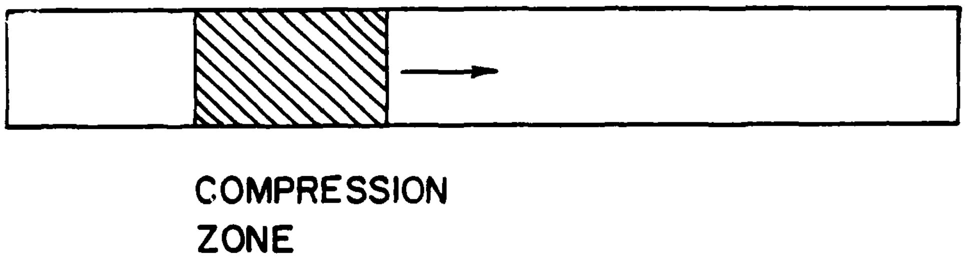


Figure 1. Schematic diagram showing the propagating compression zone in an unrestrained prismatic bar caused by a uniform comparessive force applied to the left end of the bar for a short period of time.

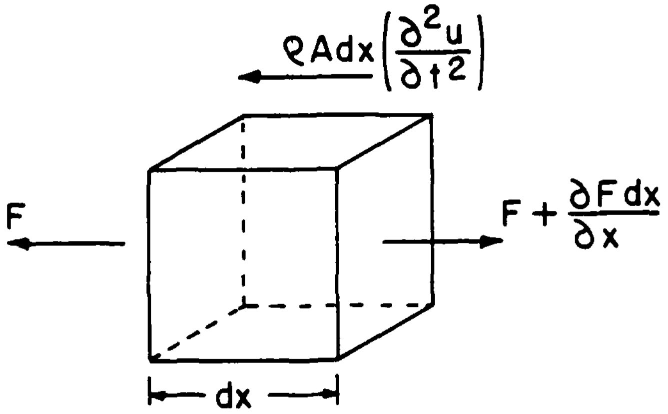


Figure 2. Free body diagram showing forces acting on differential element "dx." F denotes the force acting on the cross sectional area (A) of the element, $\partial^2u/\partial t^2$, the acceleration of the element, and p, its mass density.

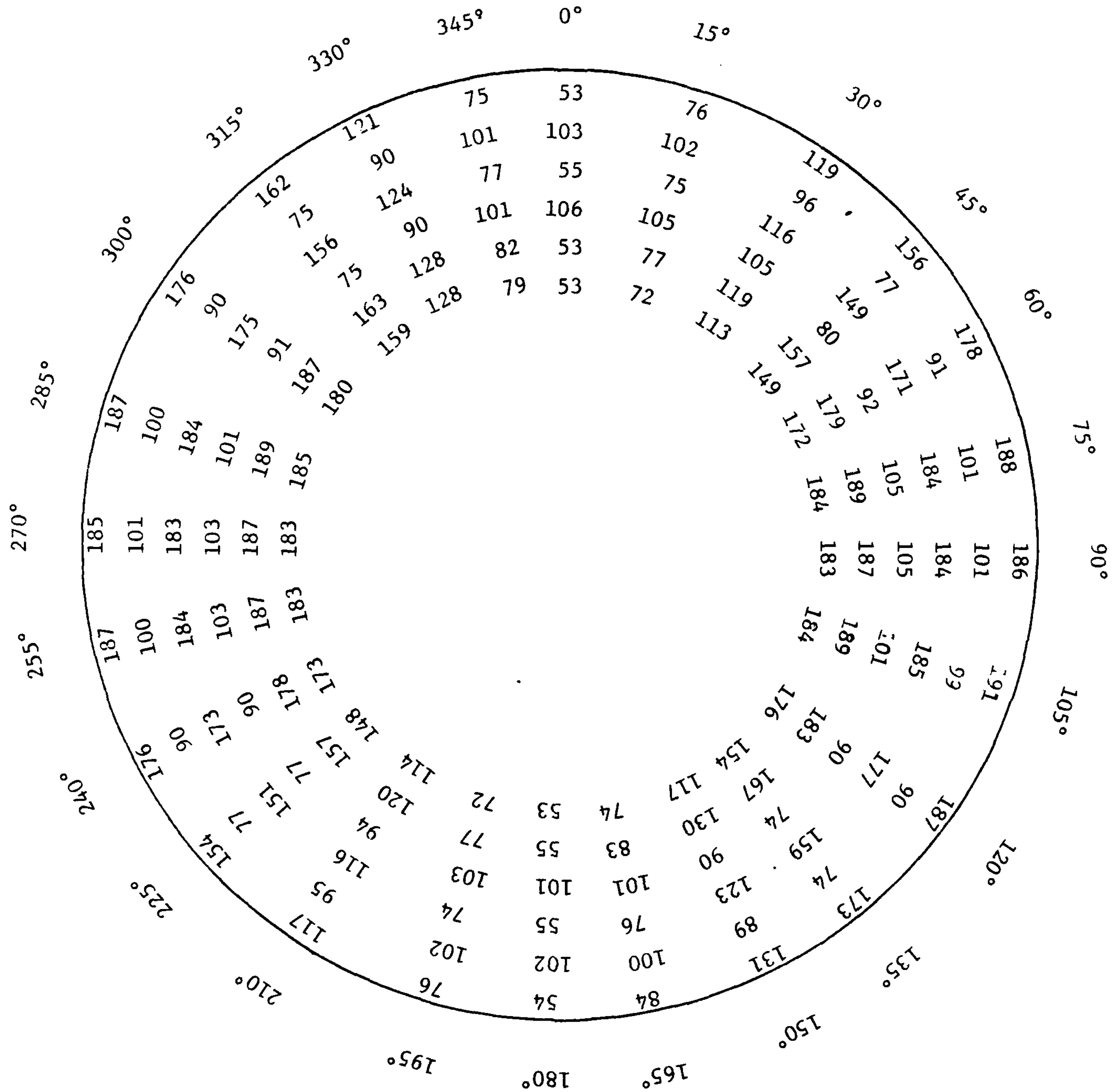


Figure 3. Stress wave times (microseconds) measured along rays of a circle 15 degrees apart. The readings were taken over the 18-inch diameter of the circle with the outermost times representing panel number 1 and sequentially thereafter so that the inner circle numbers represent panel number 6.

Panel No. 1	2	3	4	5	6
186	105	181	110	186	173
188	104	184	106	189	177
188	104	185	106	189	181
188	101	185	102	188	183
190	103	185	108	187	184
191	102	185	104	187	184
192	103	185	114	186	184
192	104	185	132	186	183
192	104	185	132	186	183

No.

Panel No.									
1	55	54	54	55	55	55	54	54	54
2	107	104	105	103	105	102	103	105	105
3	54	53	53	54	53	52	53	54	53
4	107	105	105	104	103	100	102	100	101
5	54	54	54	54	54	54	54	54	55
6	52	52	52	52	52	52	51	52	52

Figure 4. Stress wave times (microseconds) measured on 2-inch increments along the edges of the panels.

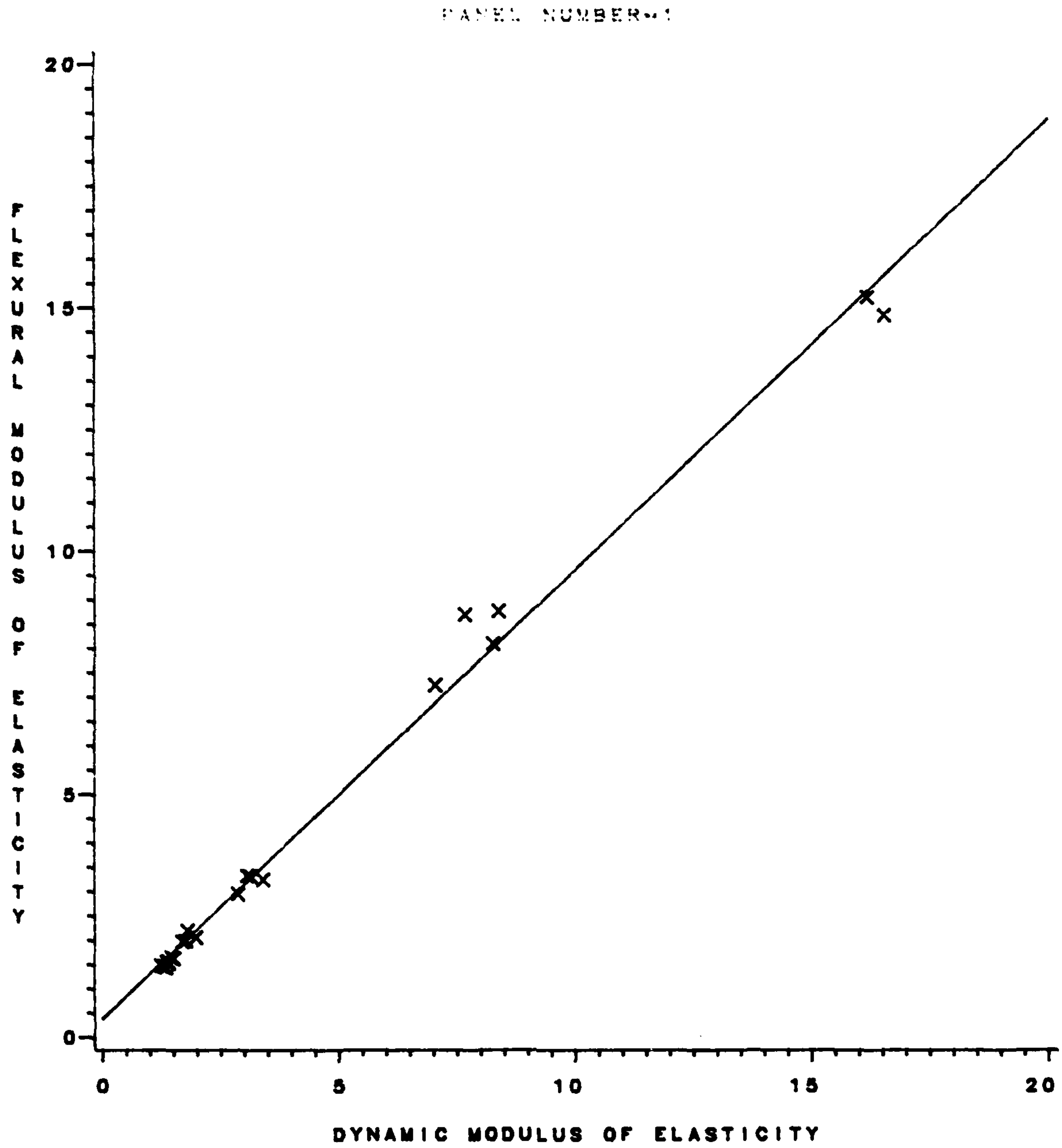


Figure 5. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - Panel 1.

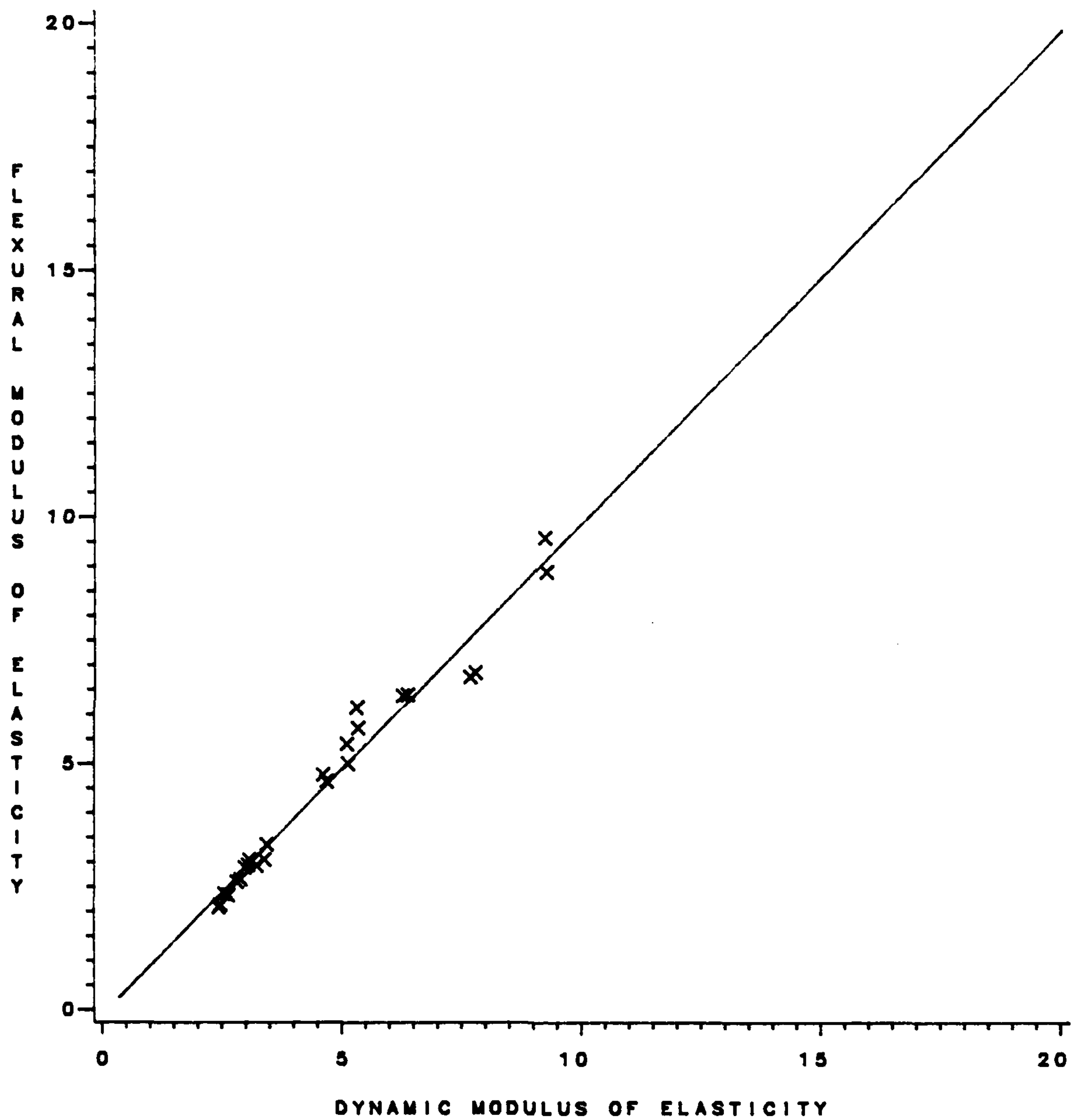


Figure 6. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - Panel 2.

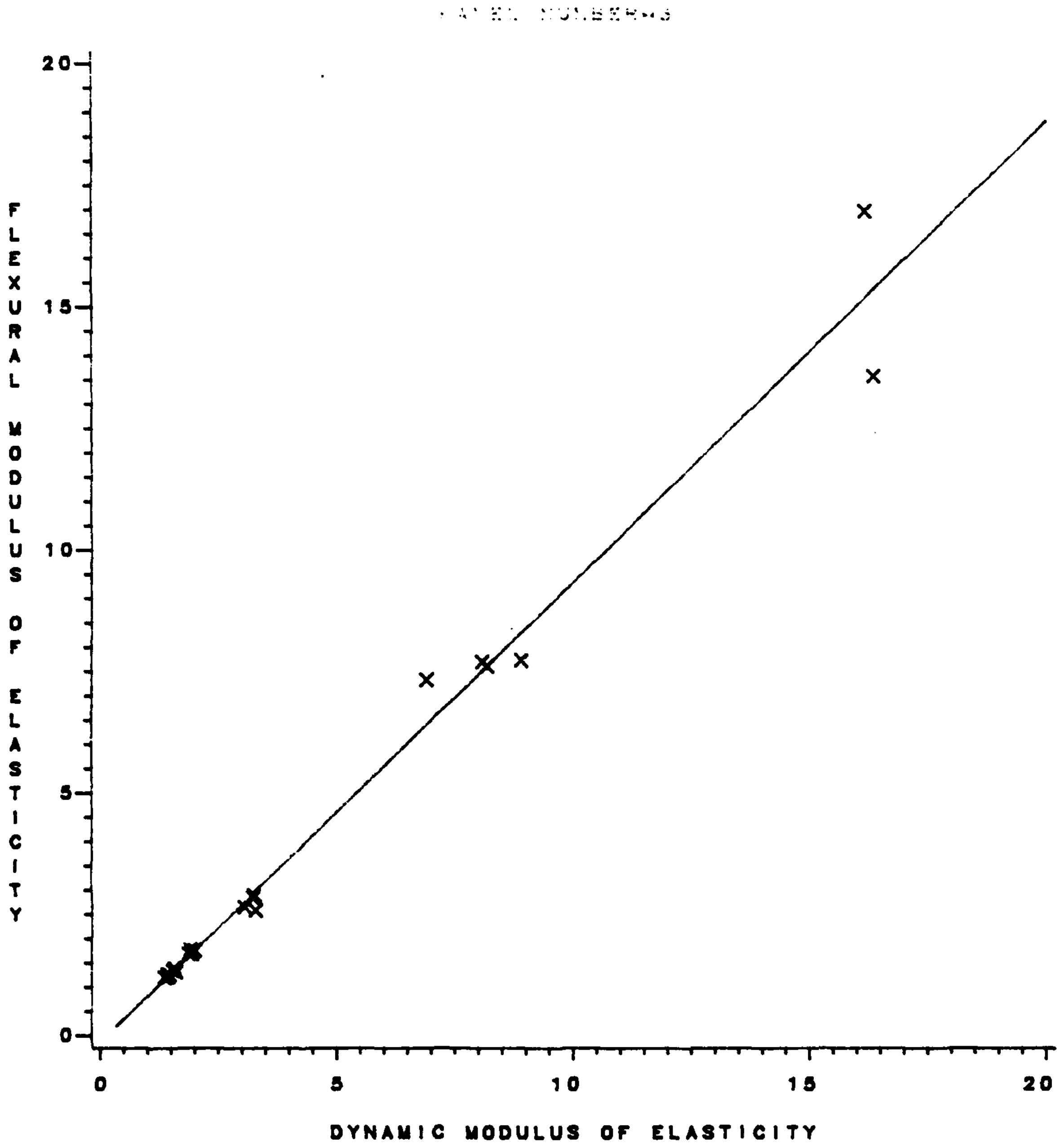


Figure 7. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - Panel 3.

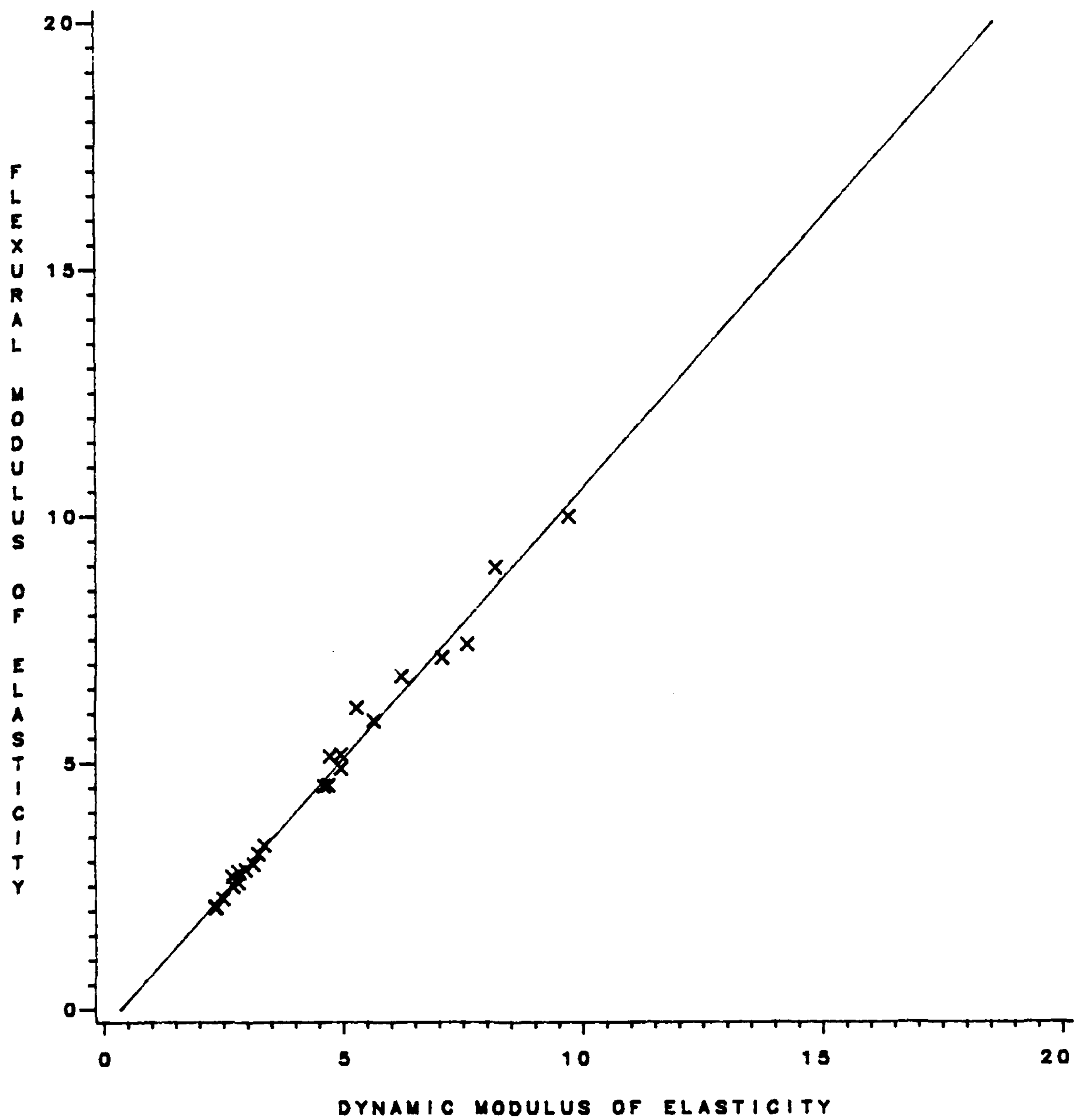


Figure 8. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - Panel 4.

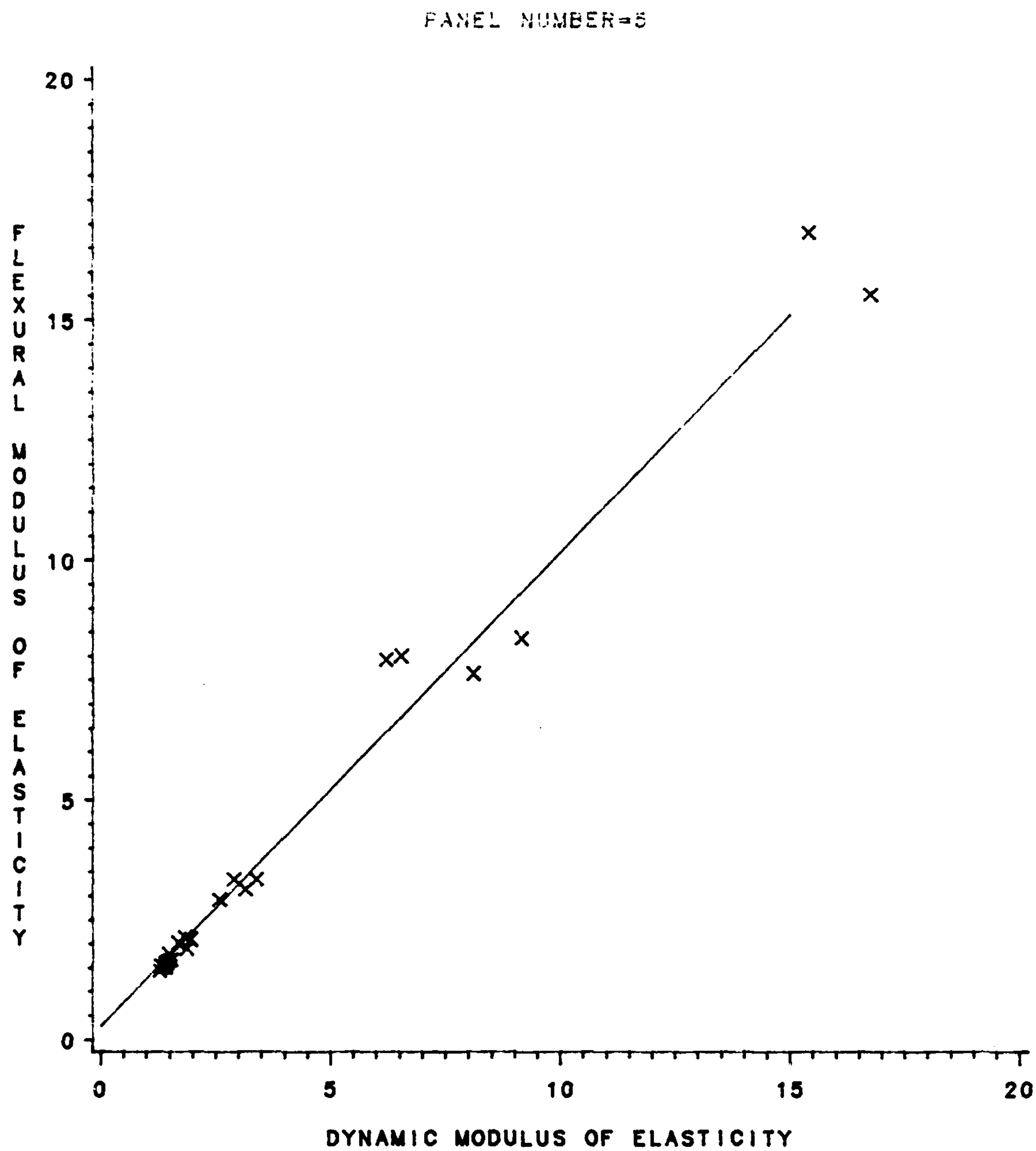


Figure 9. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - Panel 5.

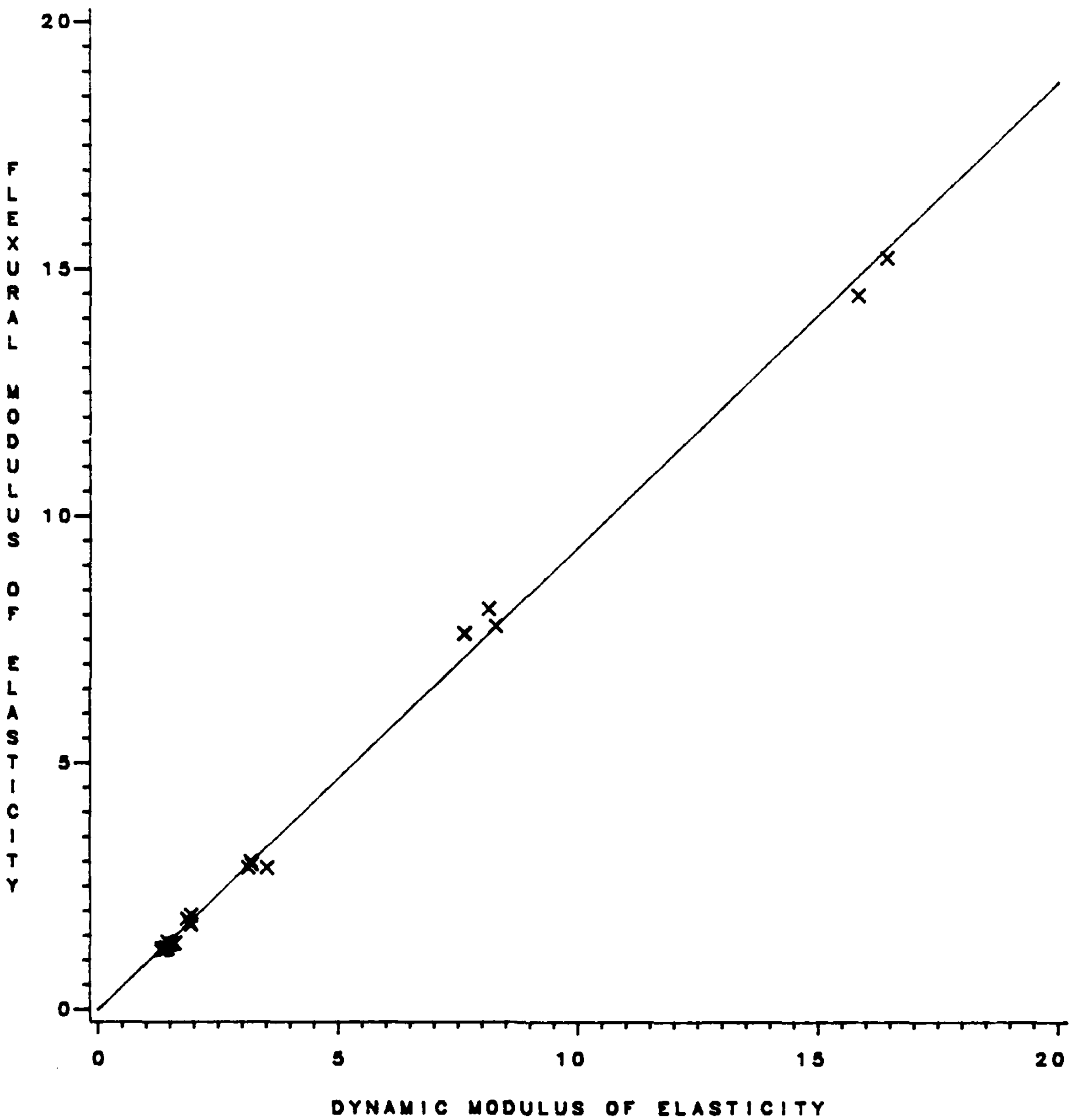


Figure 10. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - Panel 6.

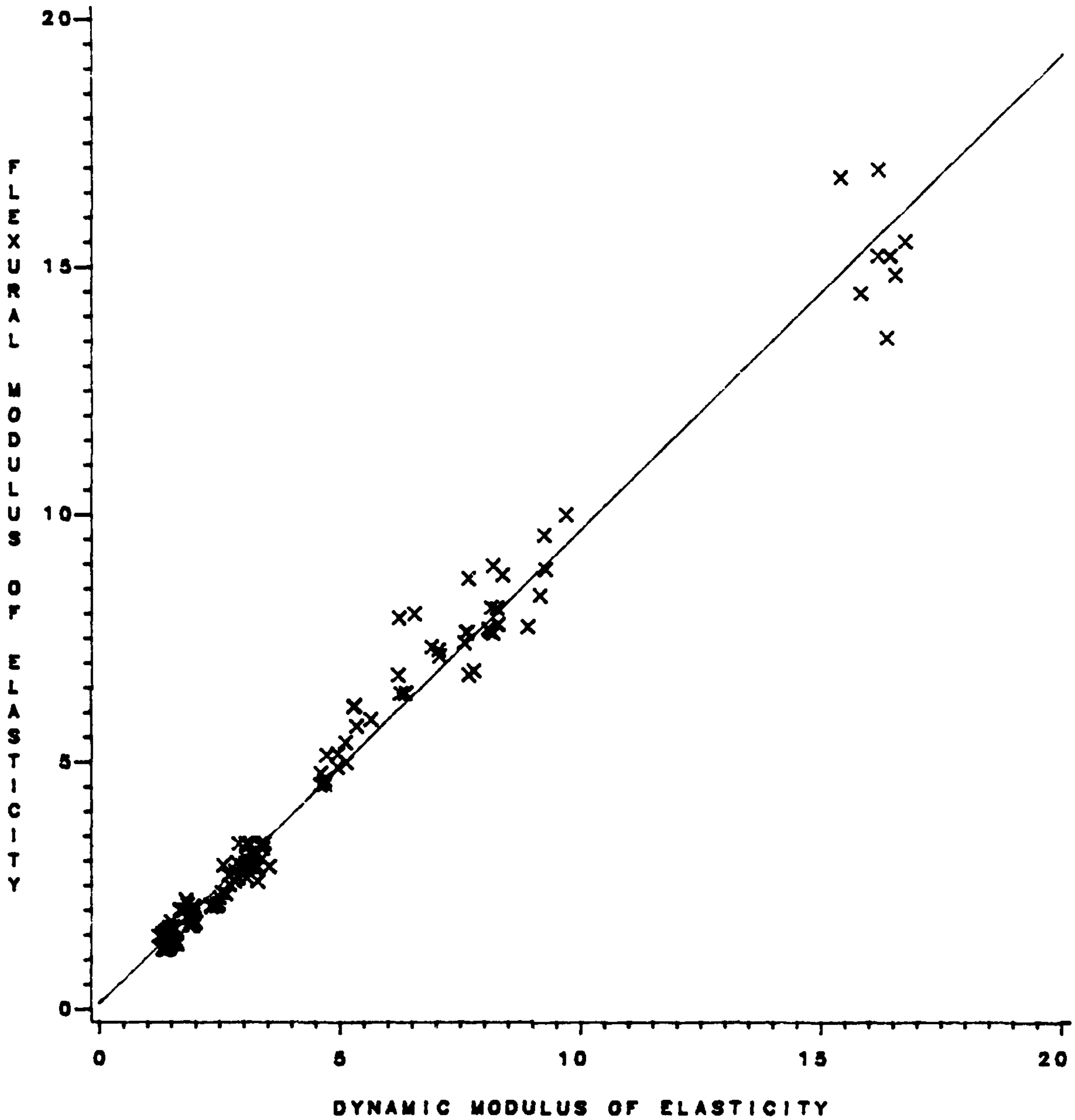


Figure 11. Scatter diagram with regression line for flexural modulus of elasticity versus dynamics modulus of elasticity - All Panels.

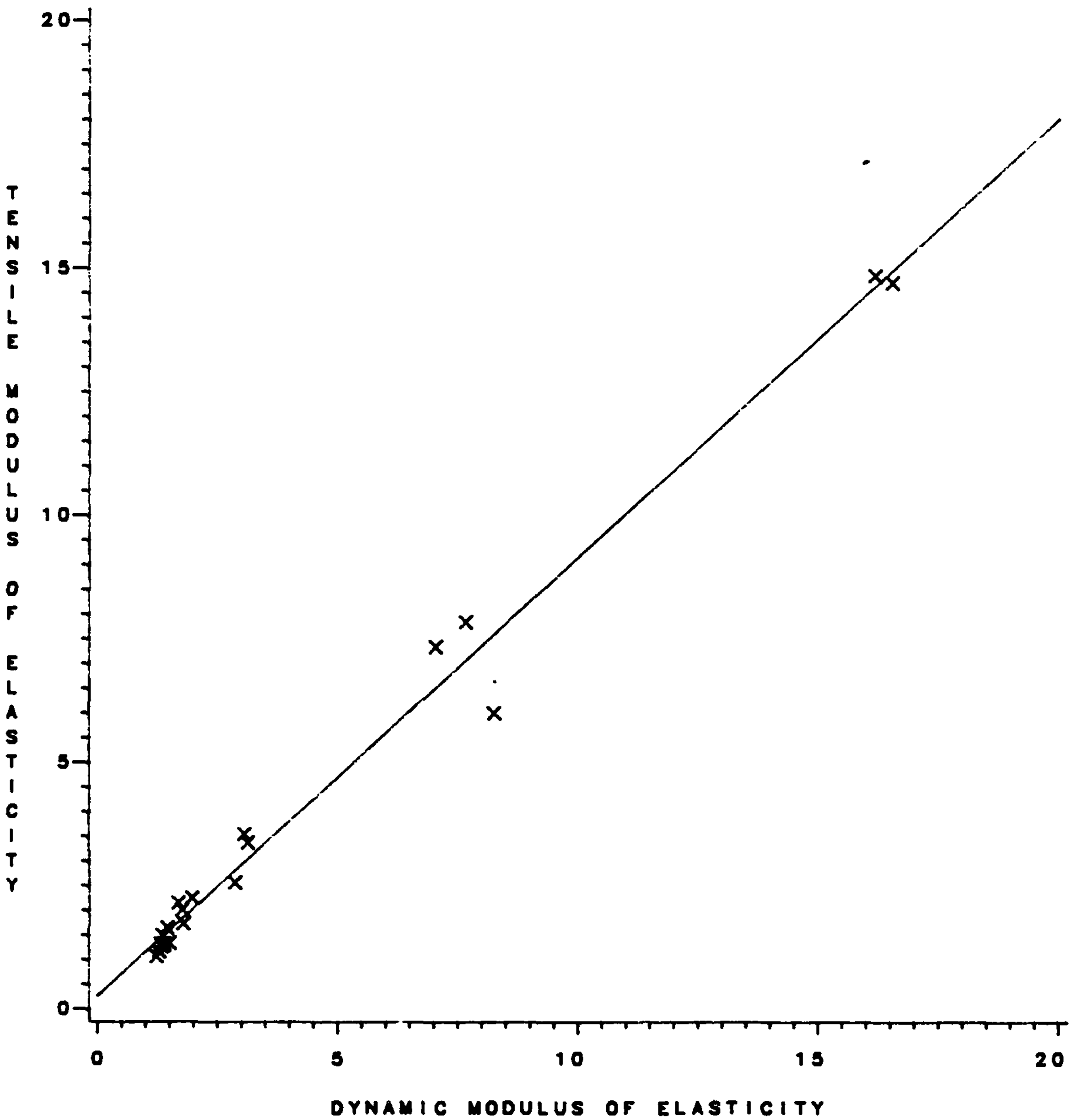


Figure 12. Scatter diagram with regression line for tensile modulus of elasticity versus dynamic modulus of elasticity - Panel 1.

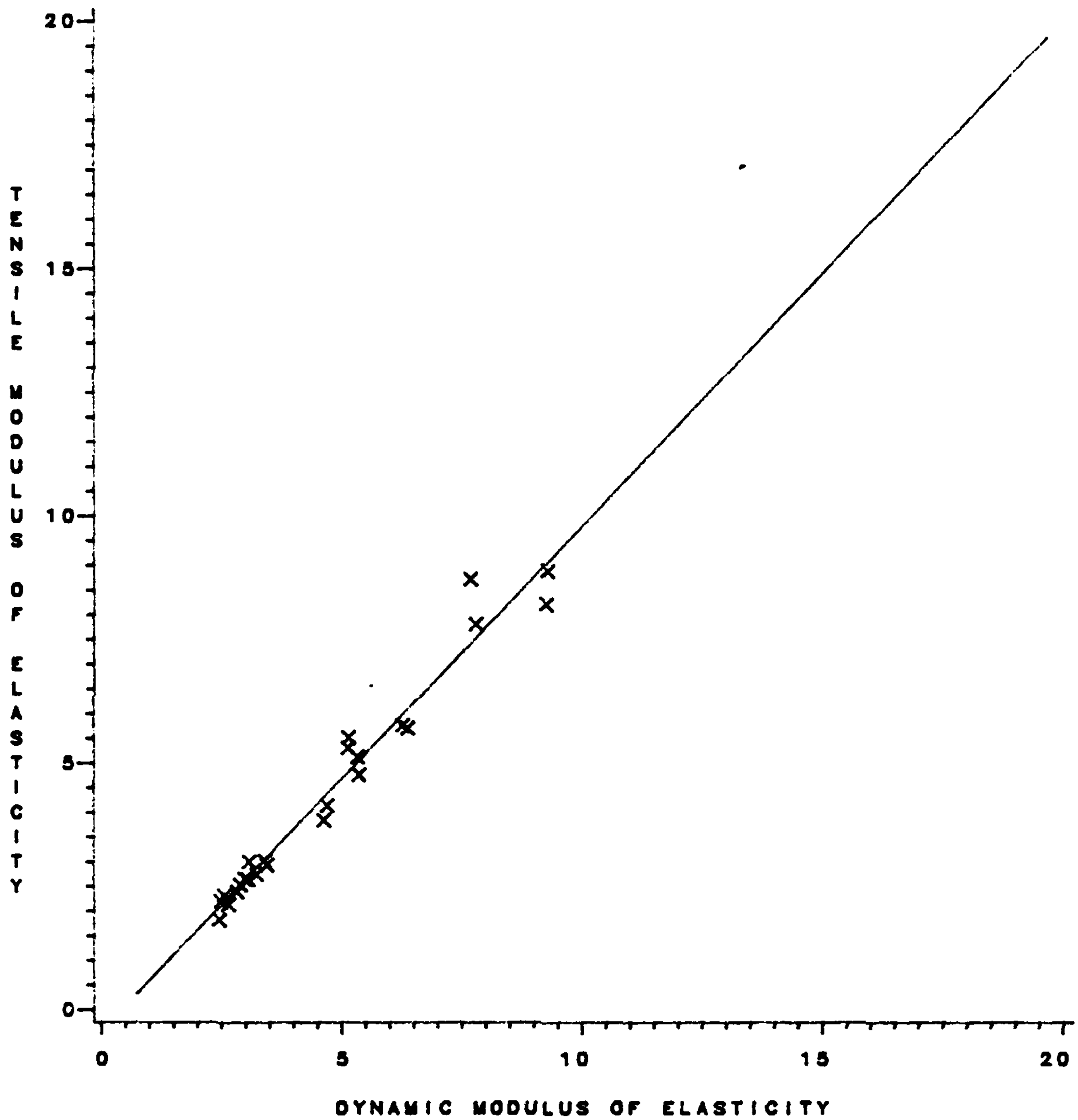


Figure 13. Scatter diagram with regression line for tensile modu. is of elasticity versus dynamic modulus of elasticity - Panel 2.

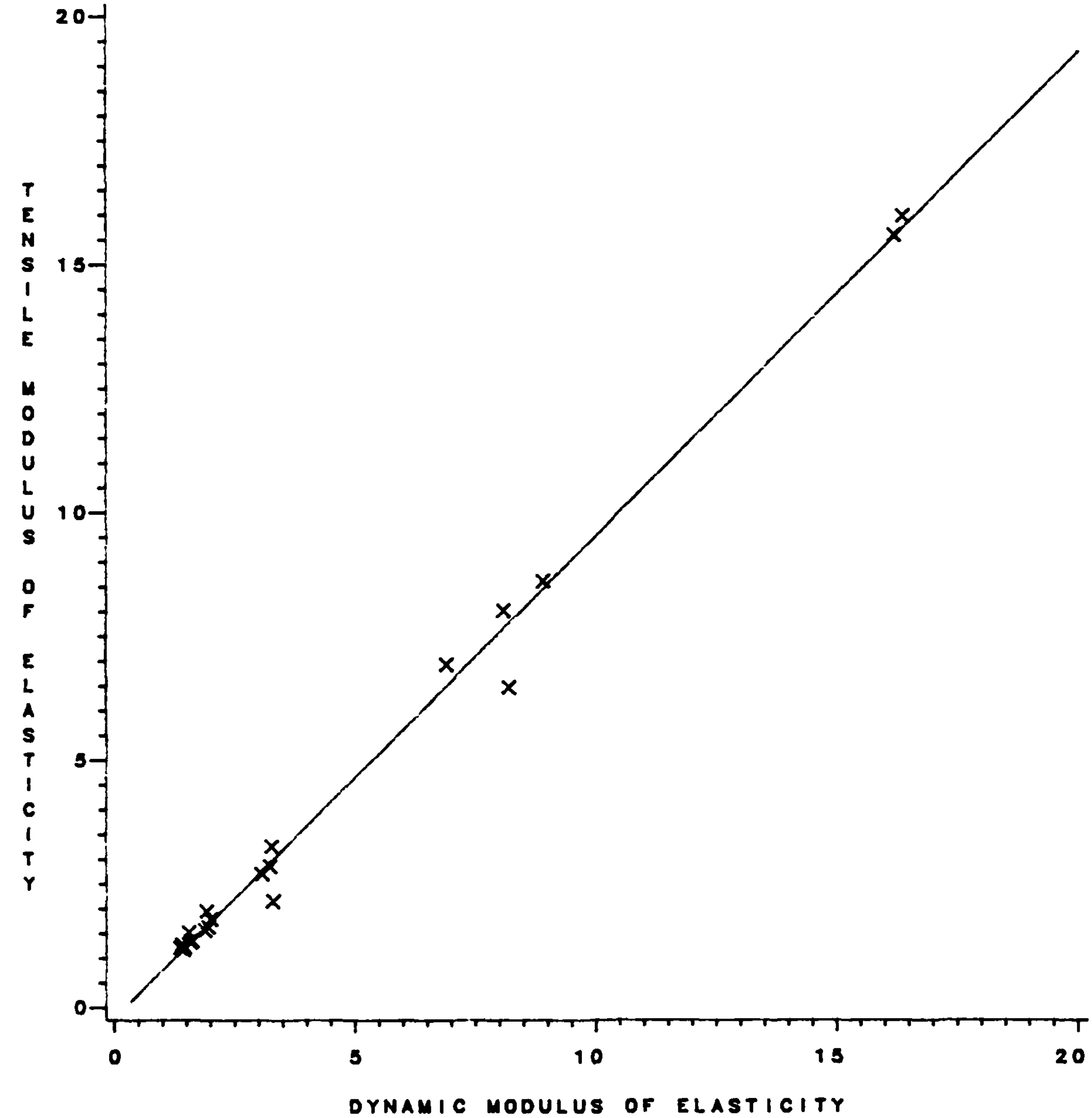


Figure 14. Scatter diagram with regression line for tensile modulus of elasticity versus dynamic modulus of elasticity - Panel 3.

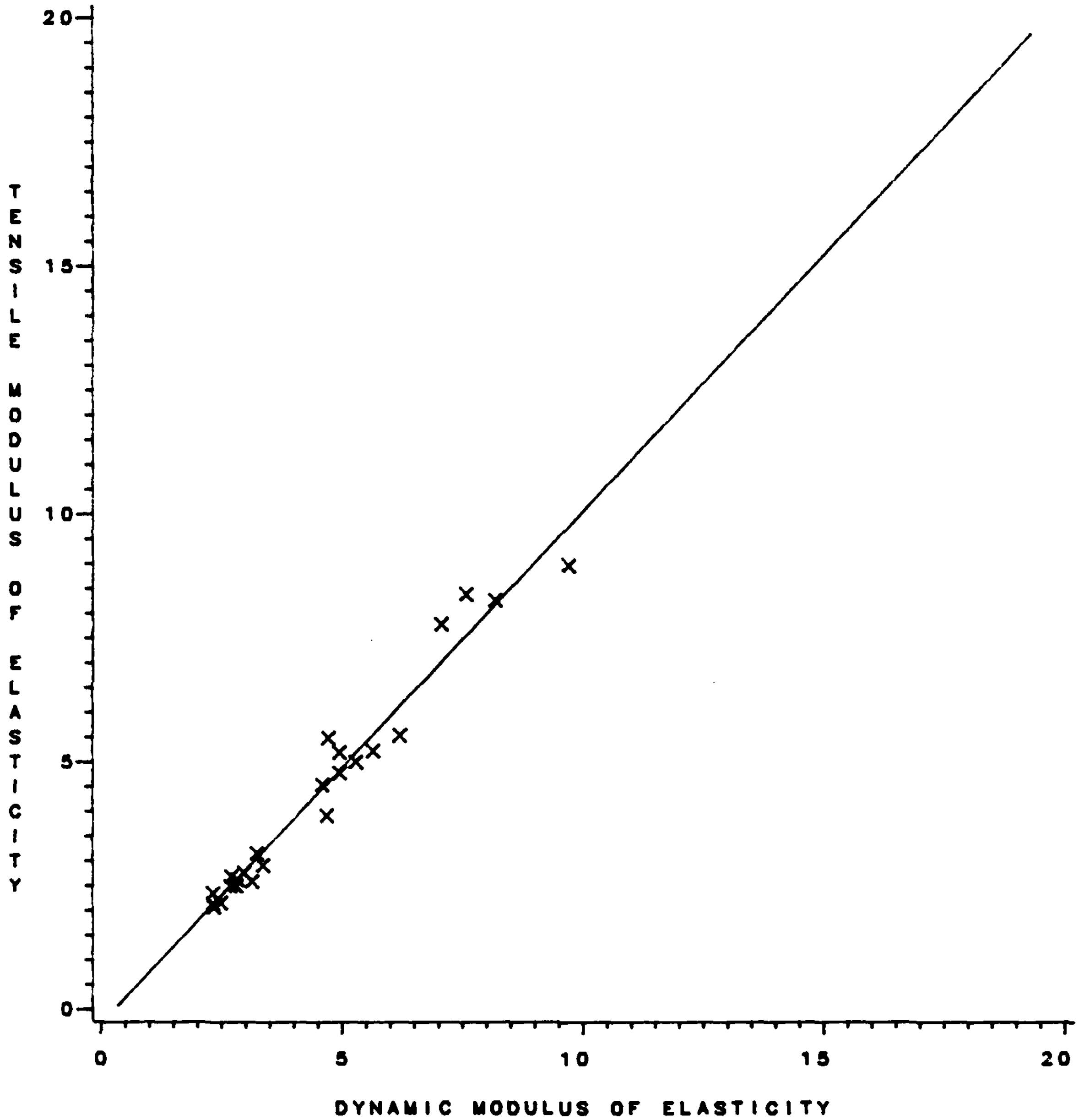


Figure 15. Scatter diagram with regression line for tensile modulus of elasticity versus dynamic modulus of elasticity - Panel 4.

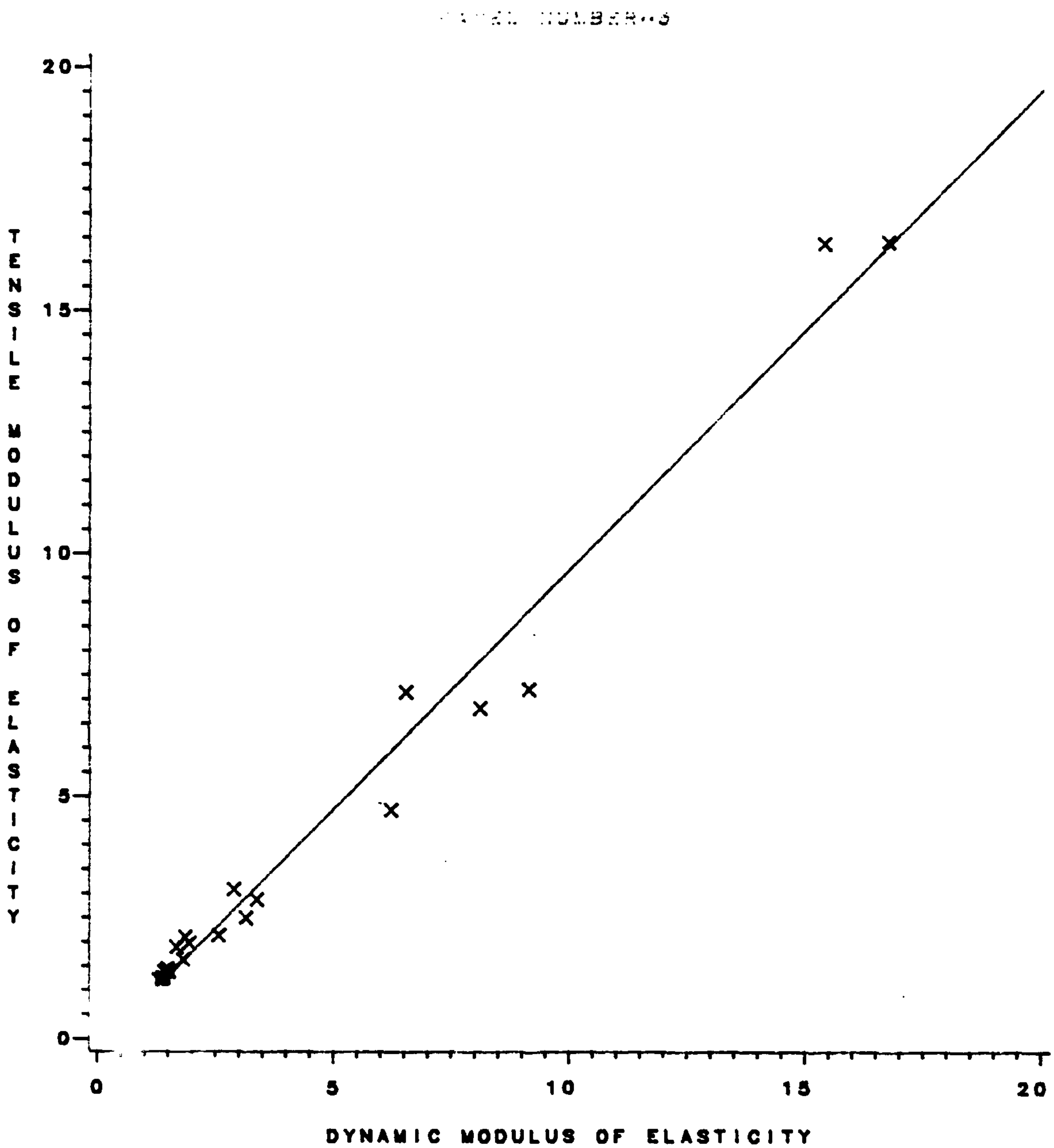


Figure 16. Scatter diagram with regression line for tensile modulus of elasticity versus dynamic modulus of elasticity - Panel 5.

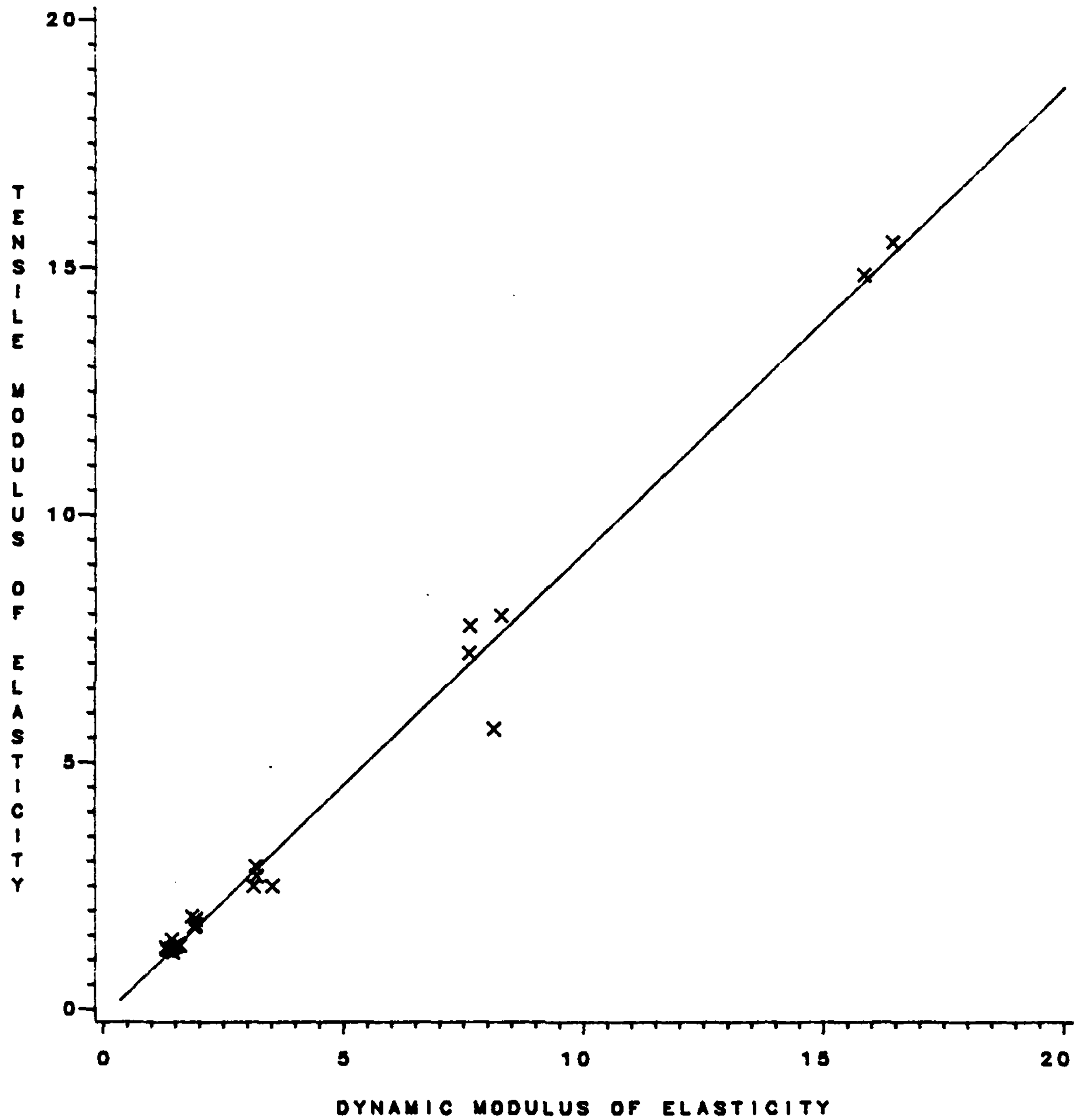


Figure 17. Scatter diagram with regression line for tensile modulus of elasticity versus dynamic modulus of elasticity - Panel 6.

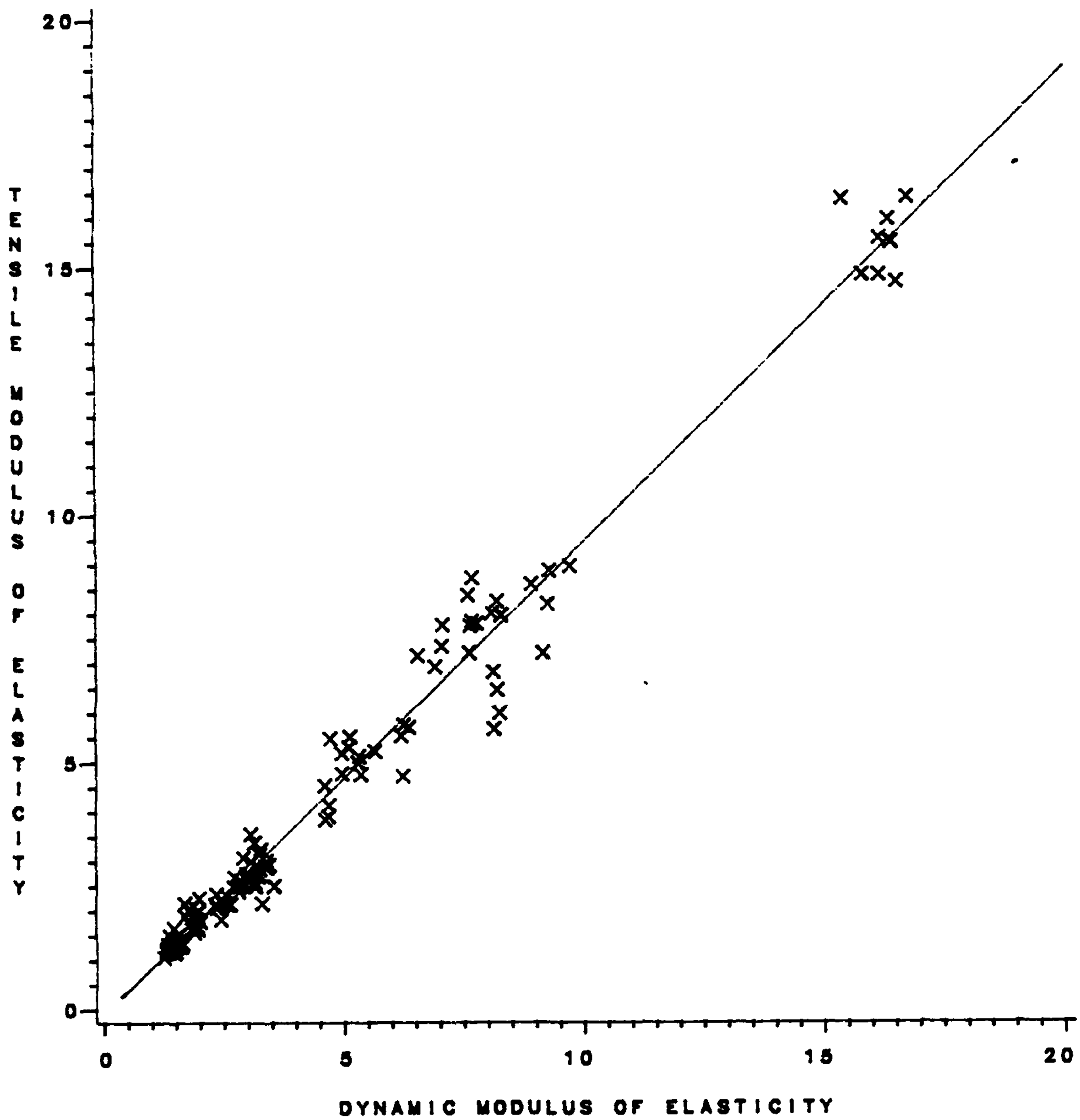


Figure 18. Scatter diagram with regression line for tensile modulus of elasticity versus dynamic modulus of elasticity - All Panels.

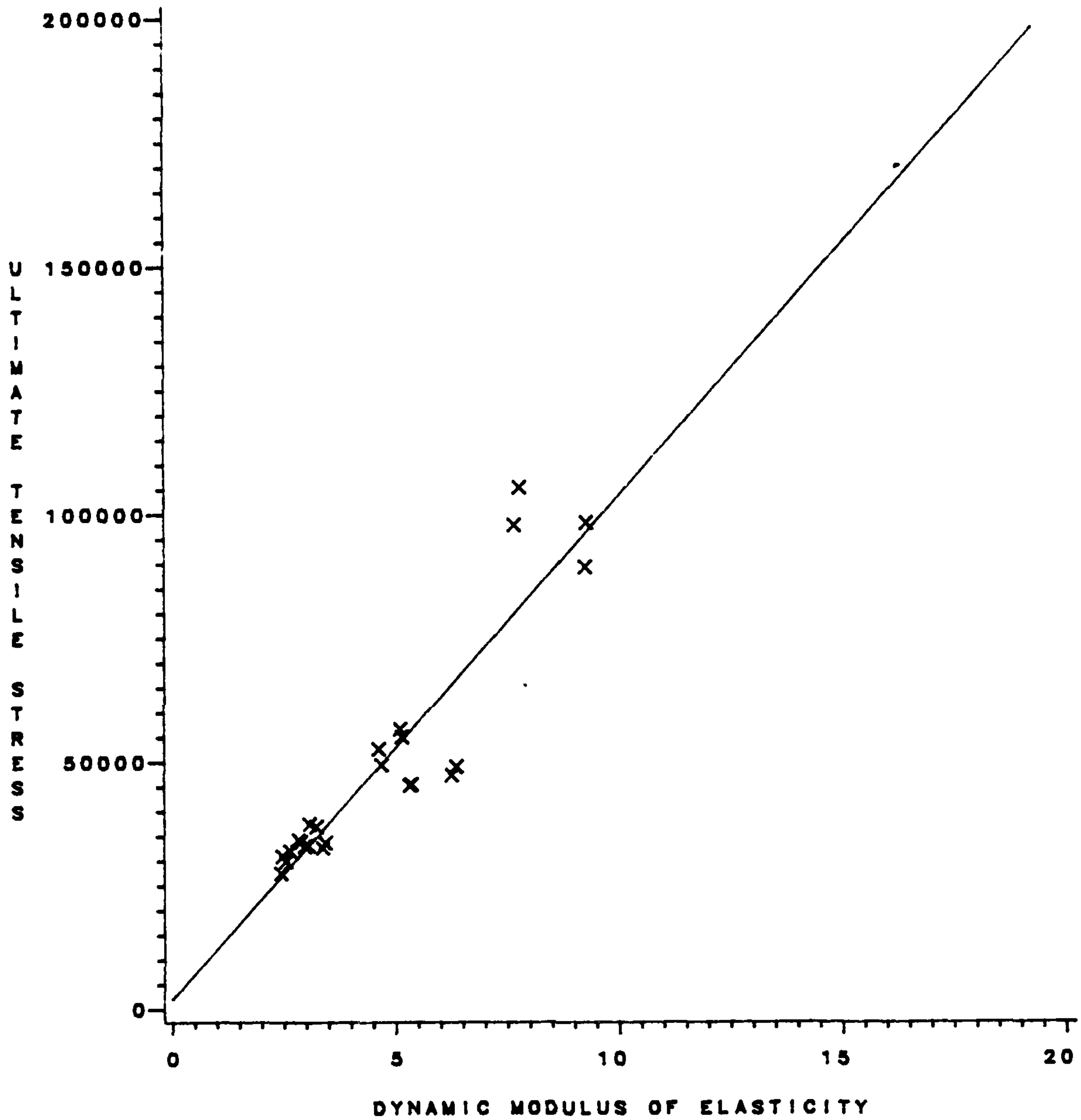


Figure 19. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panel 2.

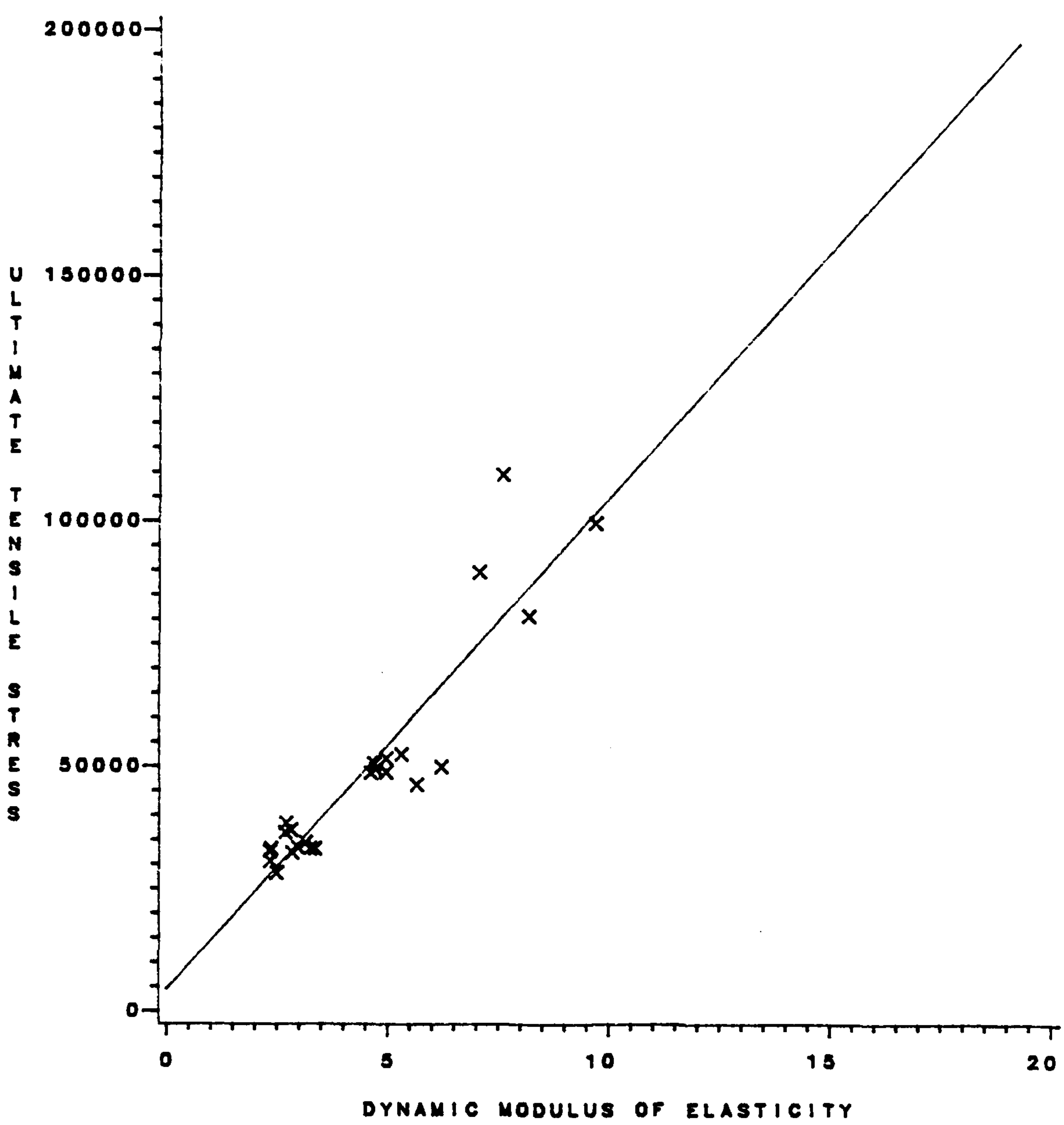


Figure 20. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panel 4.

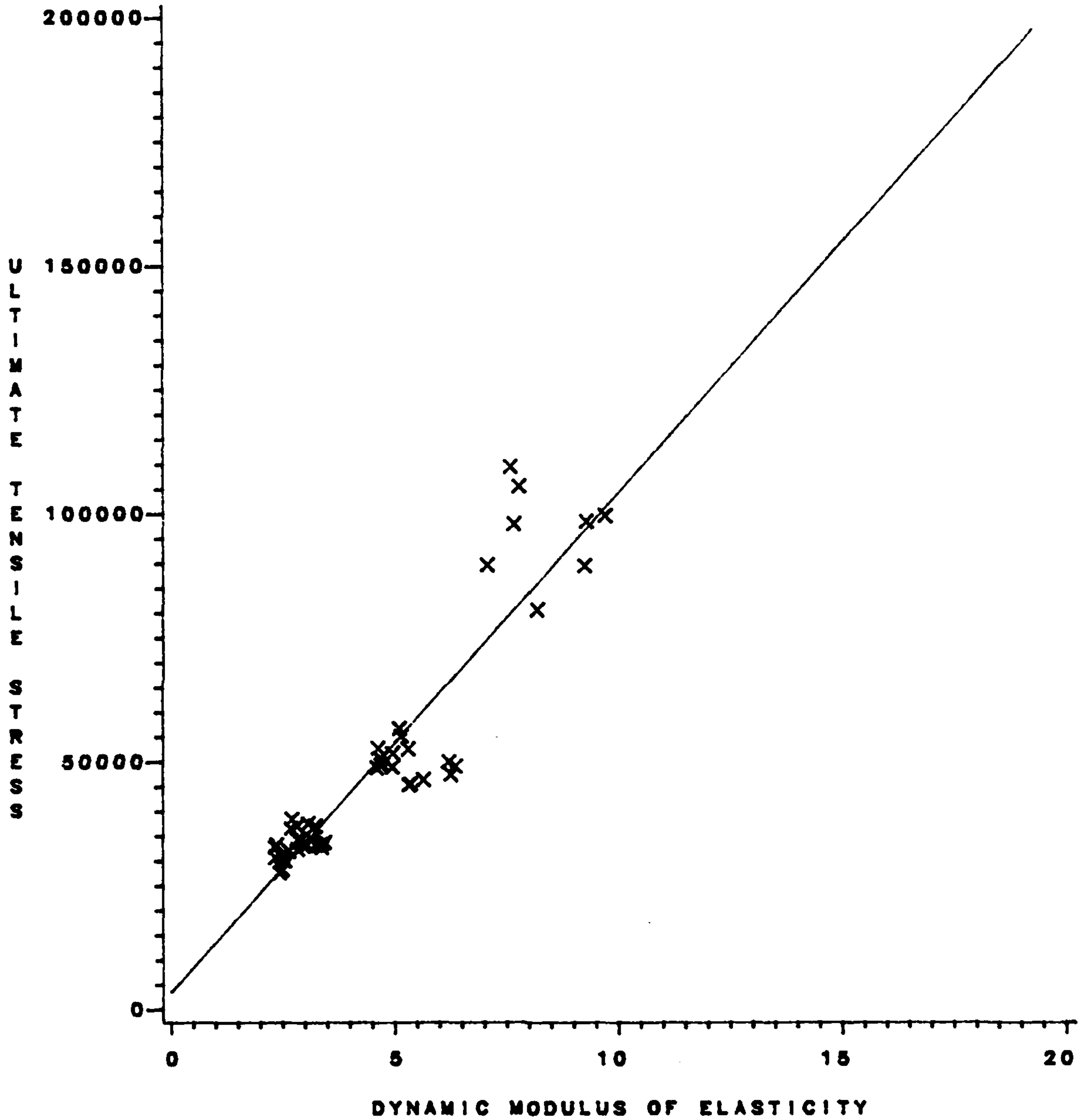


Figure 21. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panels 2 and 4.

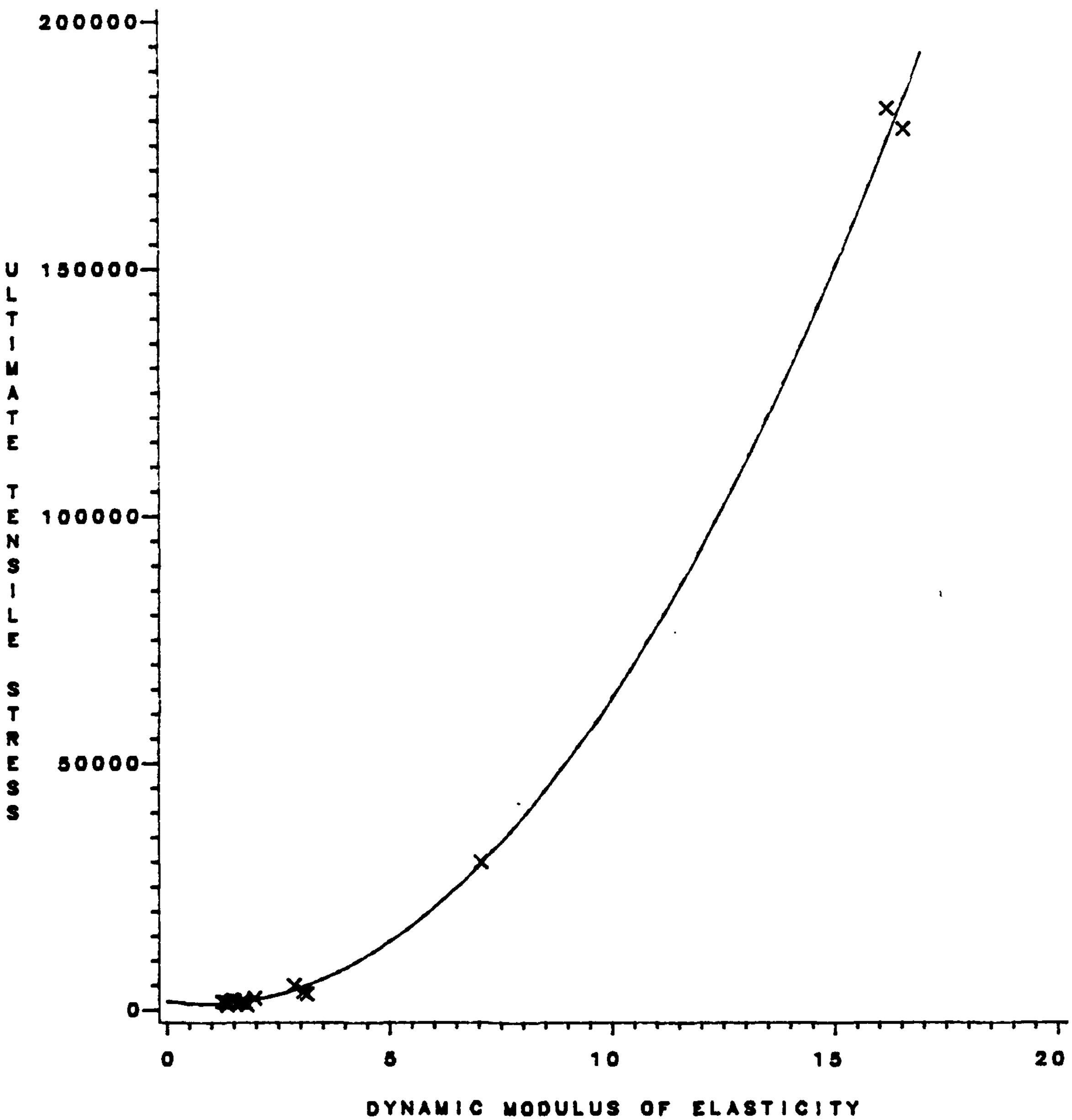


Figure 22. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panel 1.

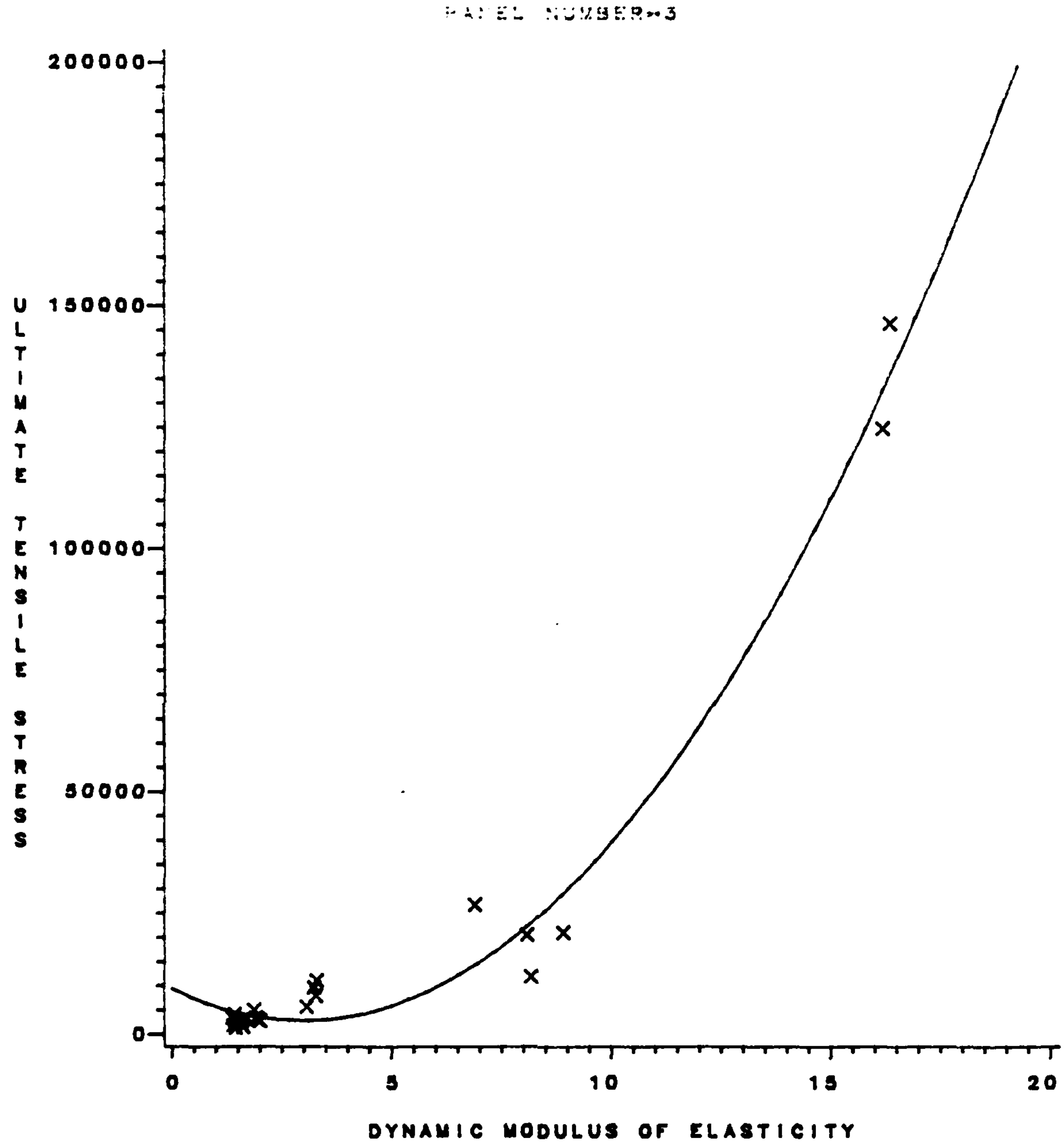


Figure 23. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panel 3.

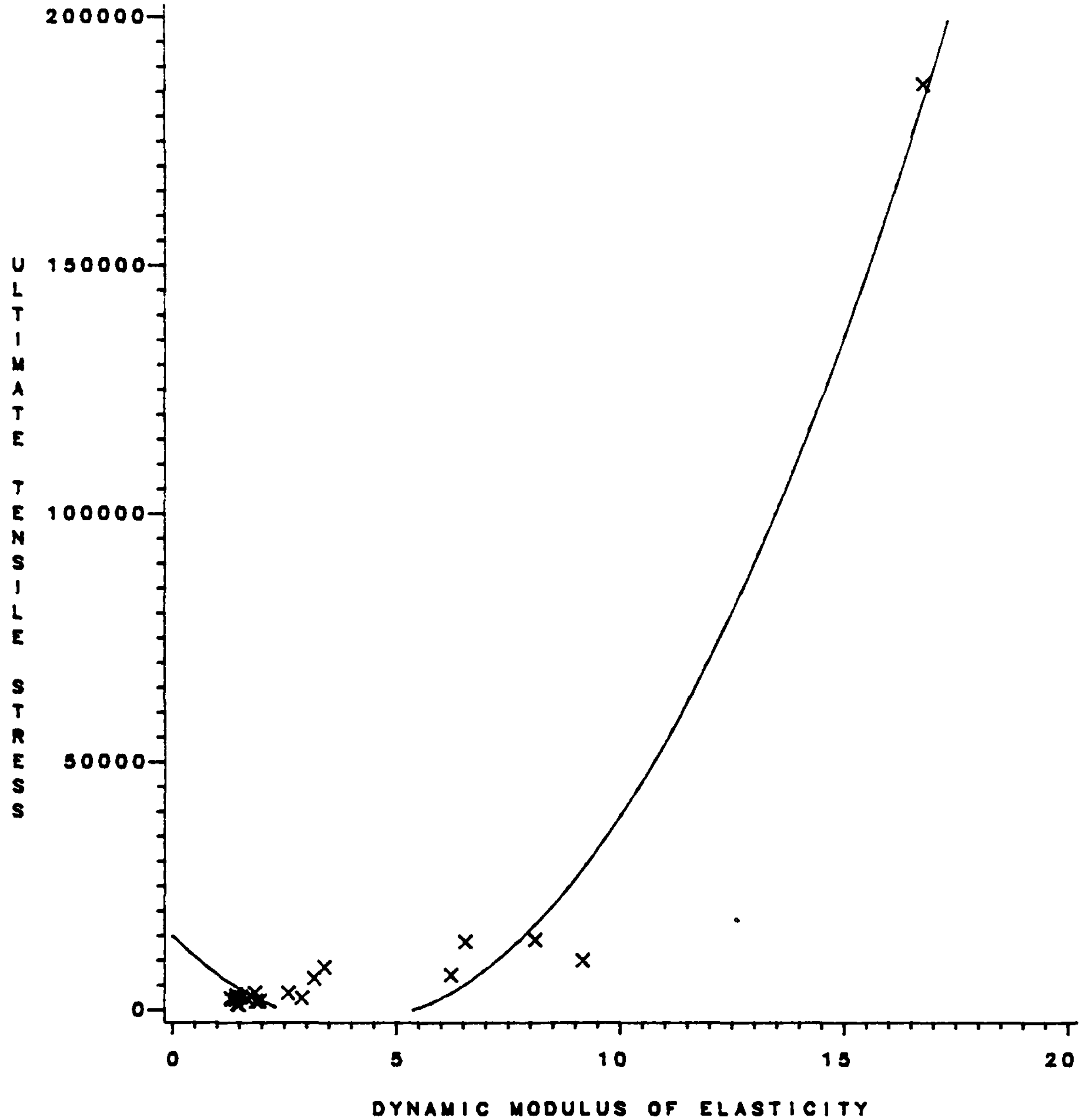


Figure 24. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panel 5.

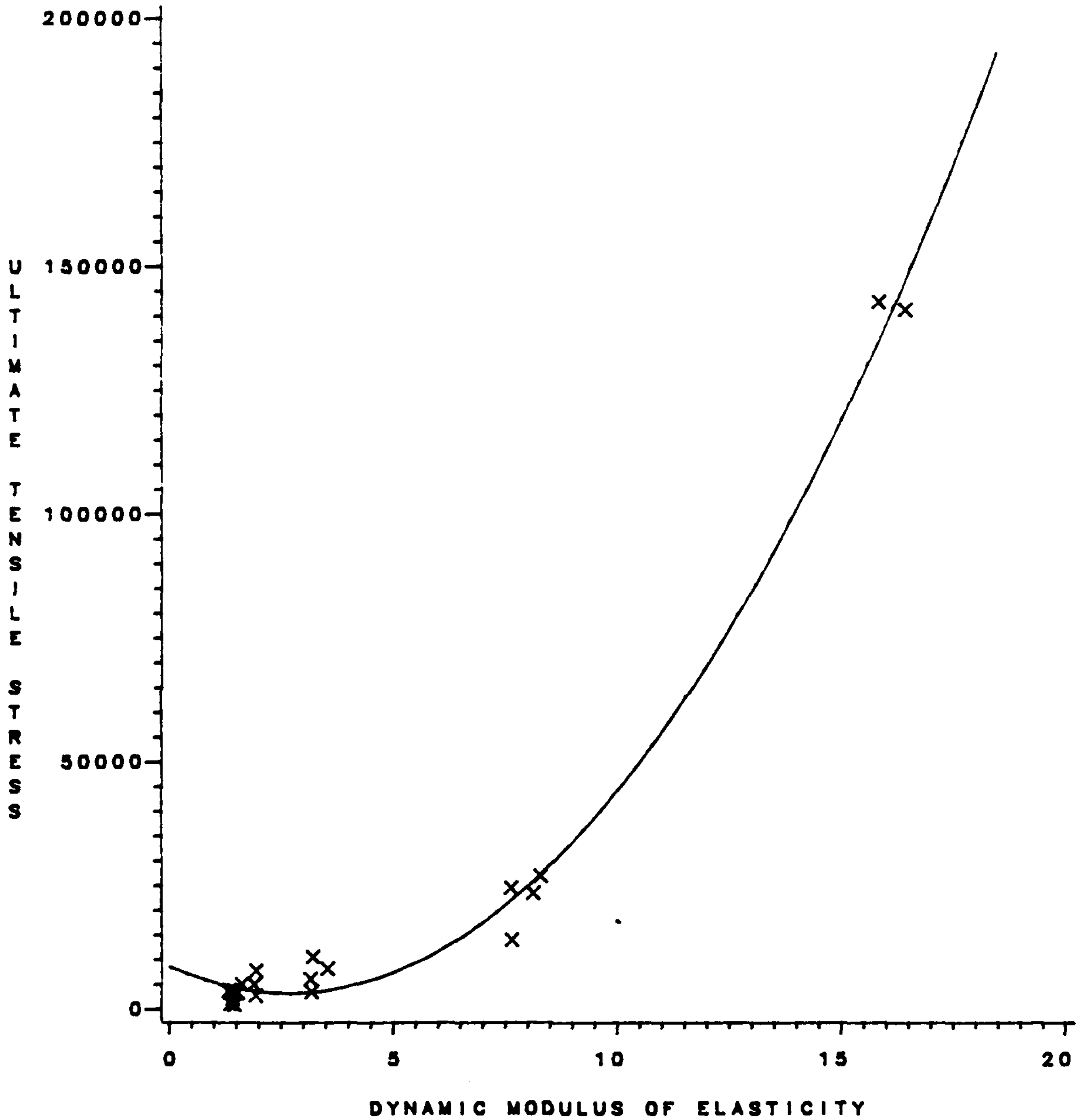


Figure 25. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panel 6.

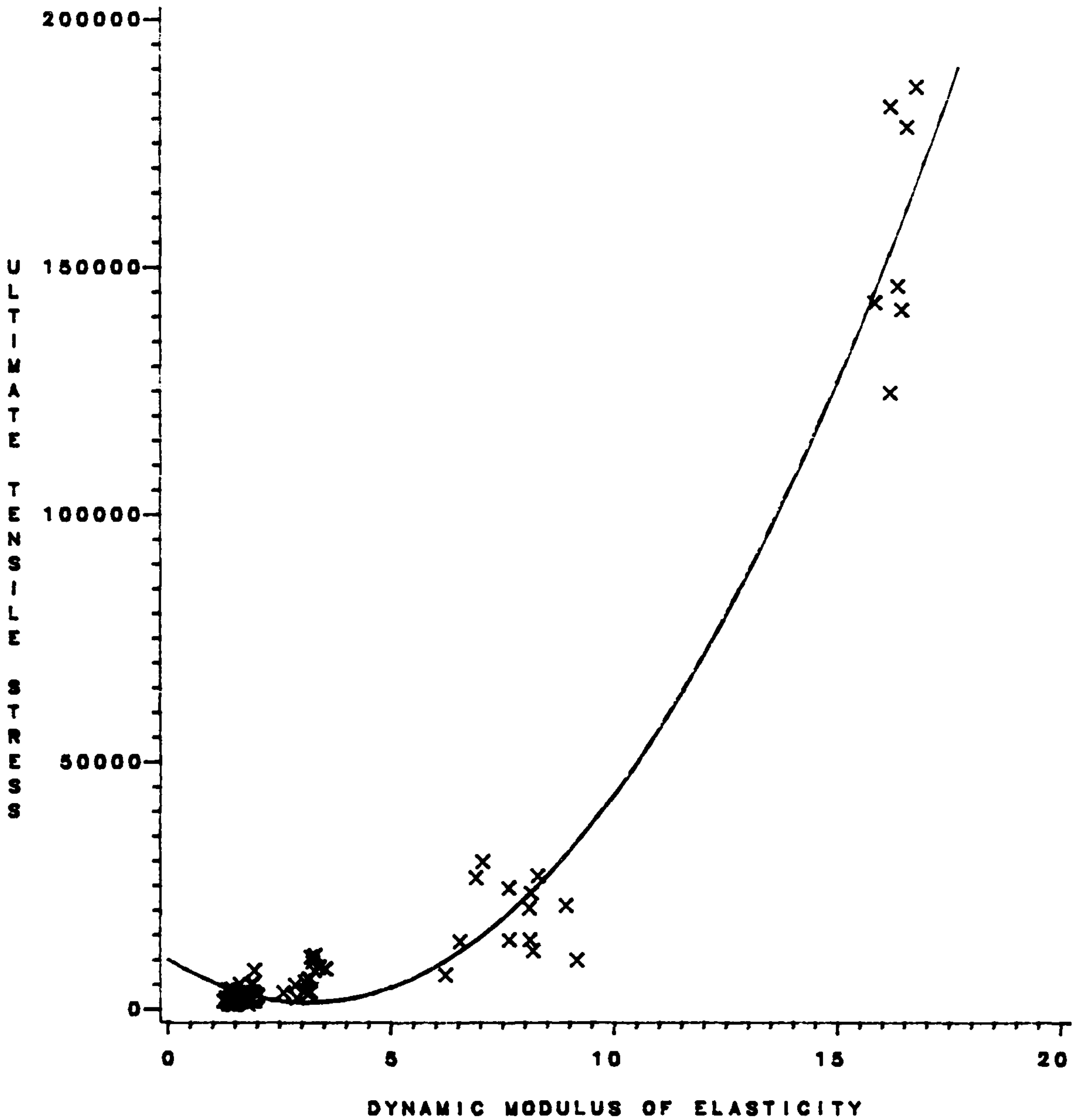


Figure 26. Scatter diagram with regression line for ultimate tensile stress versus dynamic modulus of elasticity - Panels 1, 3, 5, and 6.

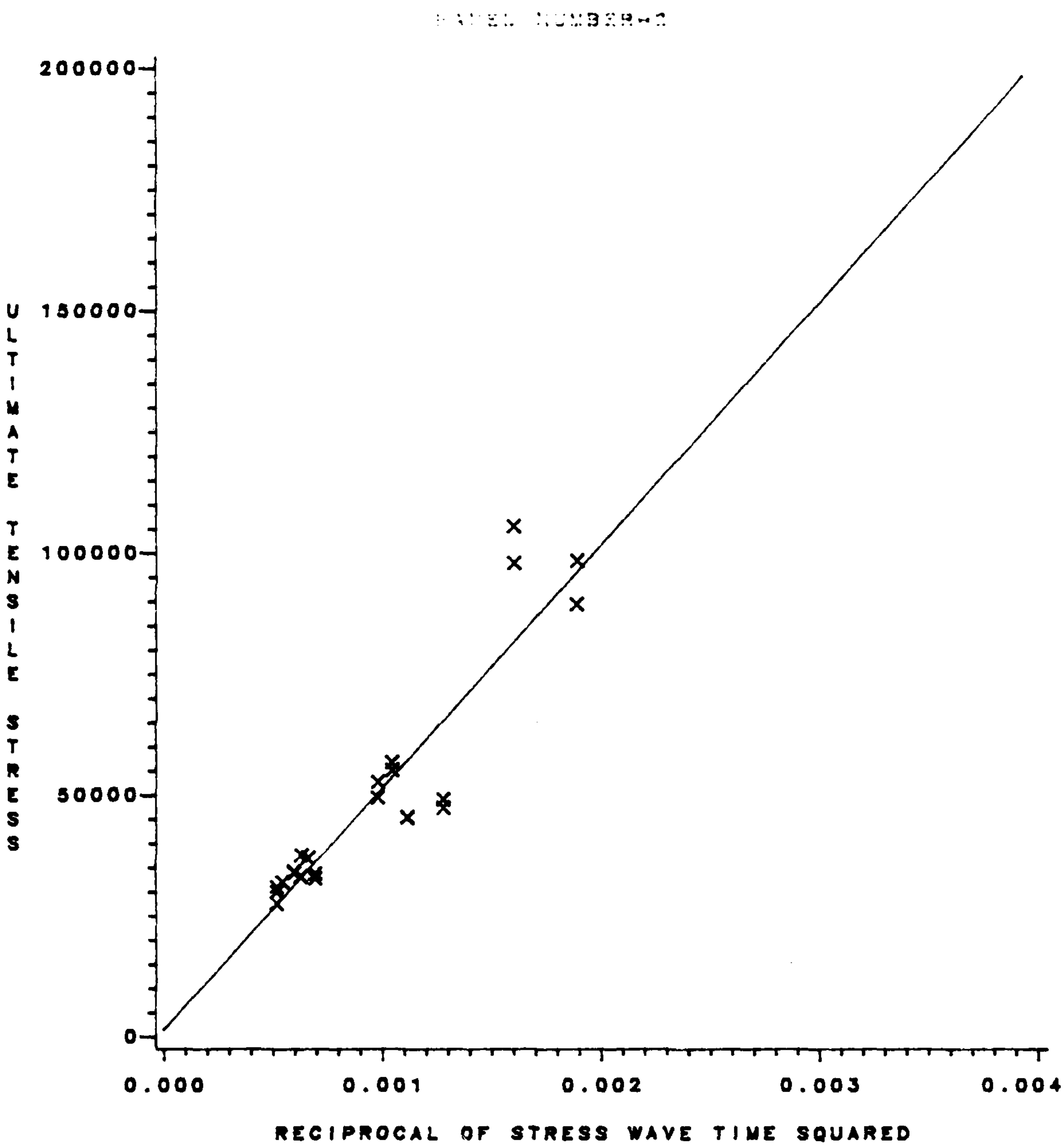


Figure 27. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panel 2.

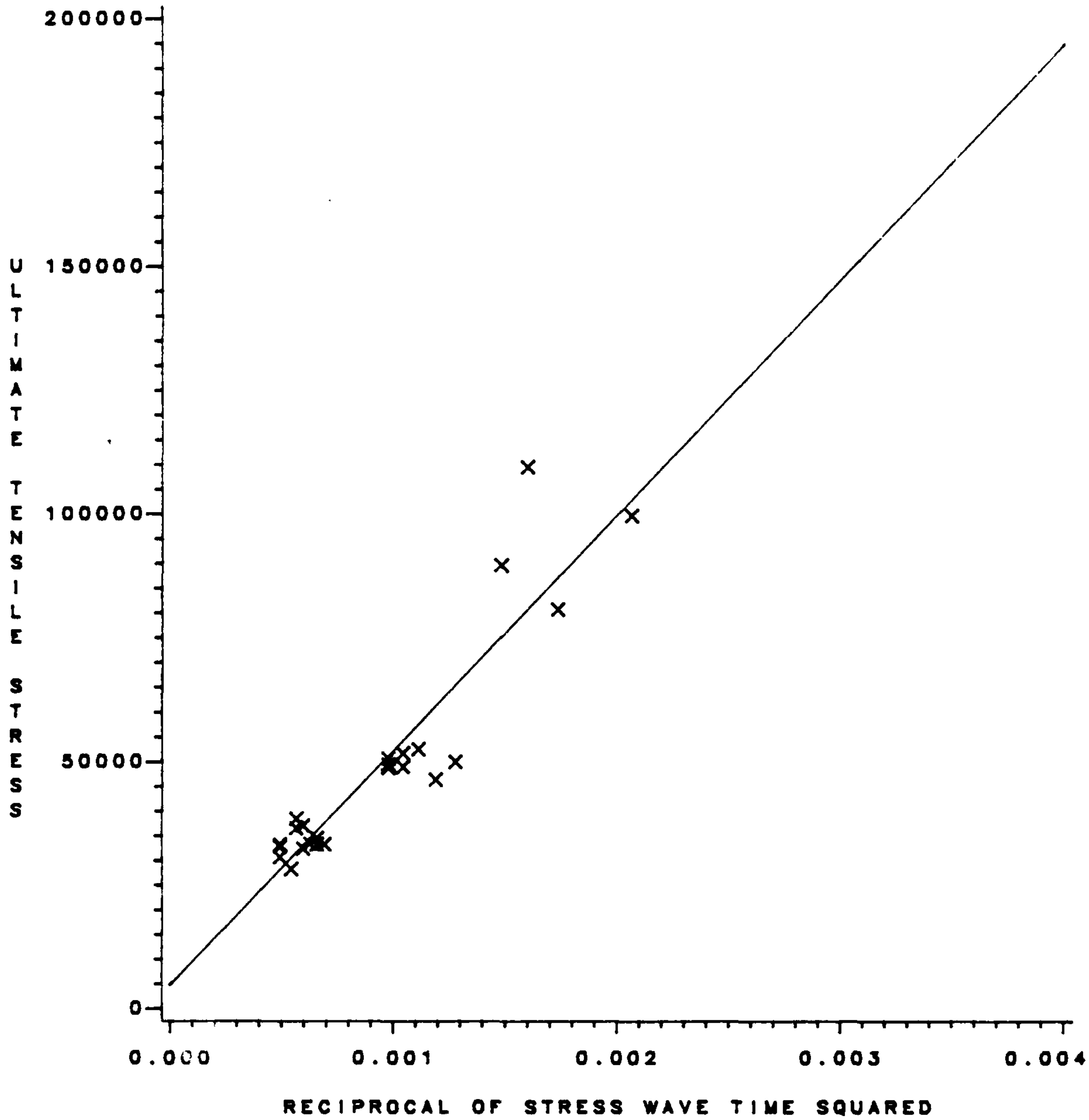


Figure 28. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panel 4.

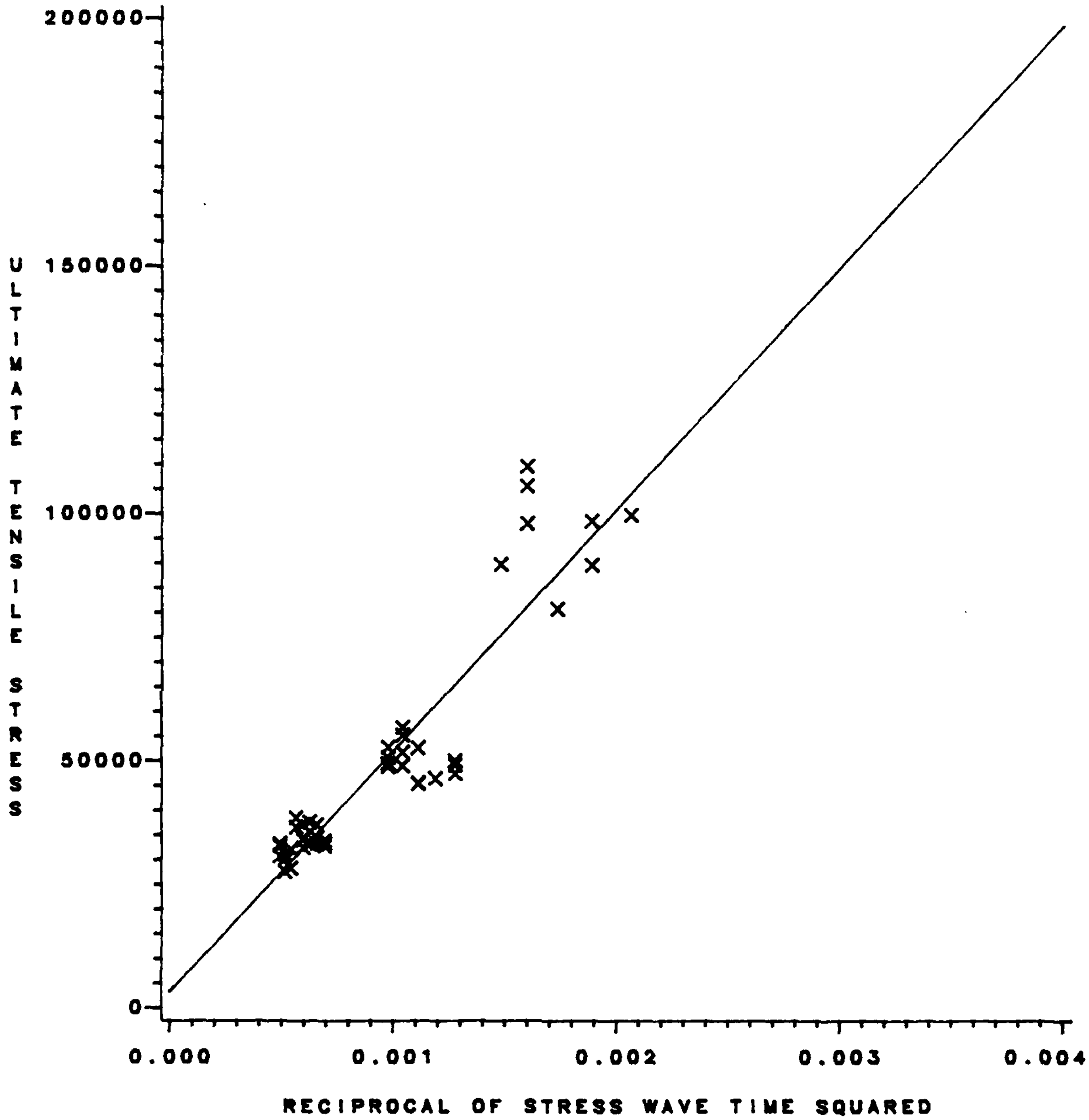


Figure 29. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panels 2 and 4.

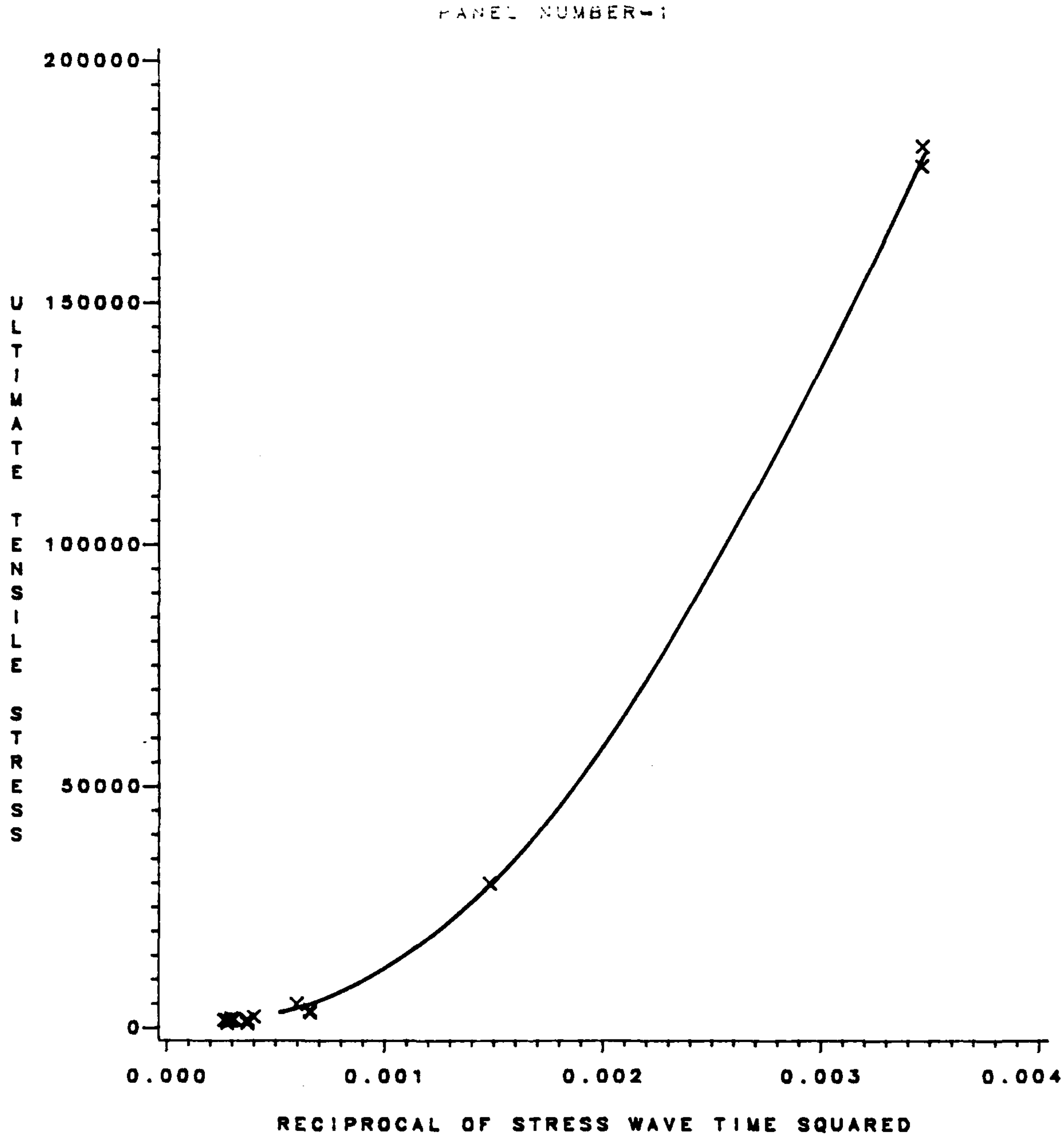


Figure 30. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panel 1.

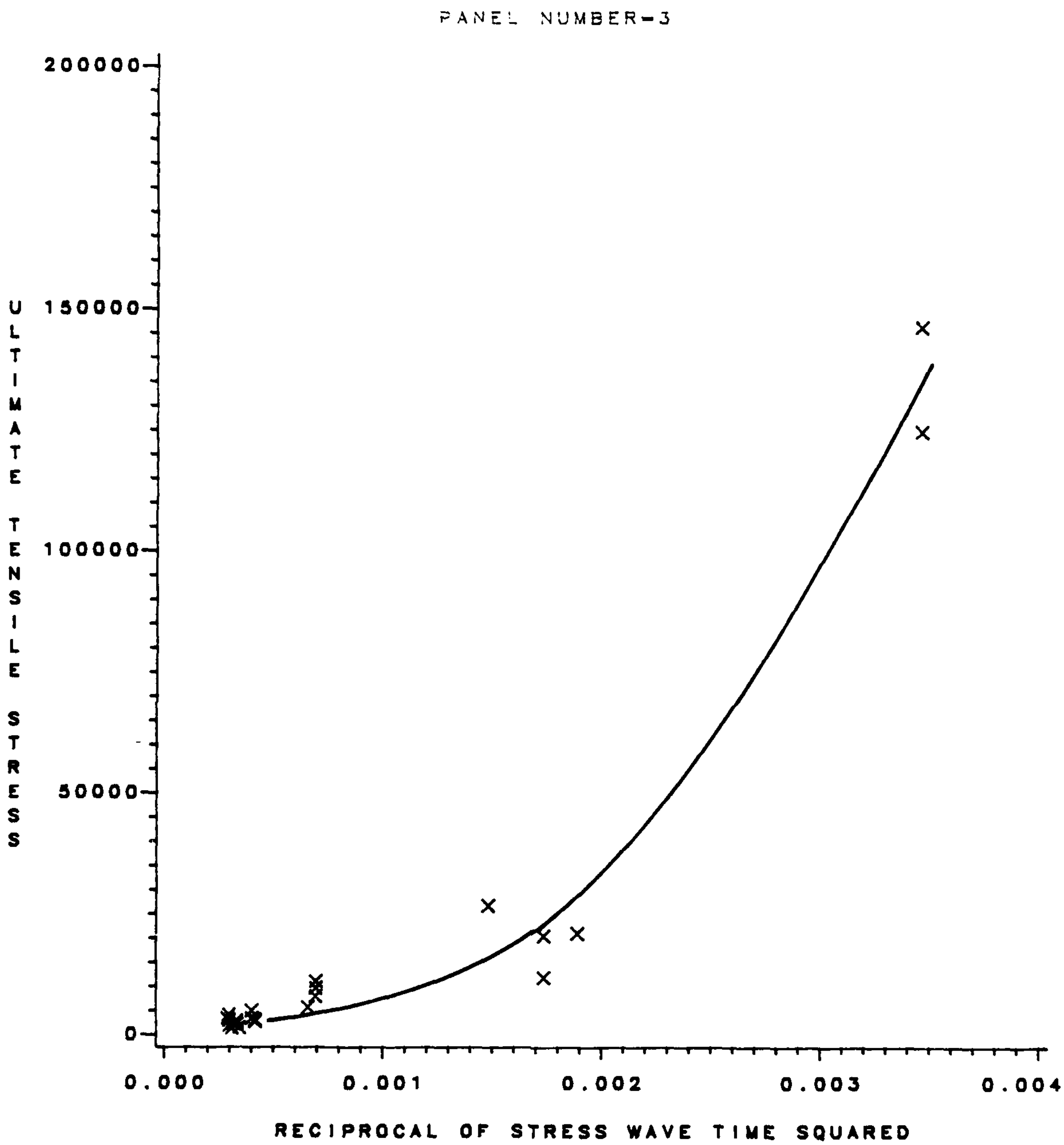


Figure 31. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panel 3.

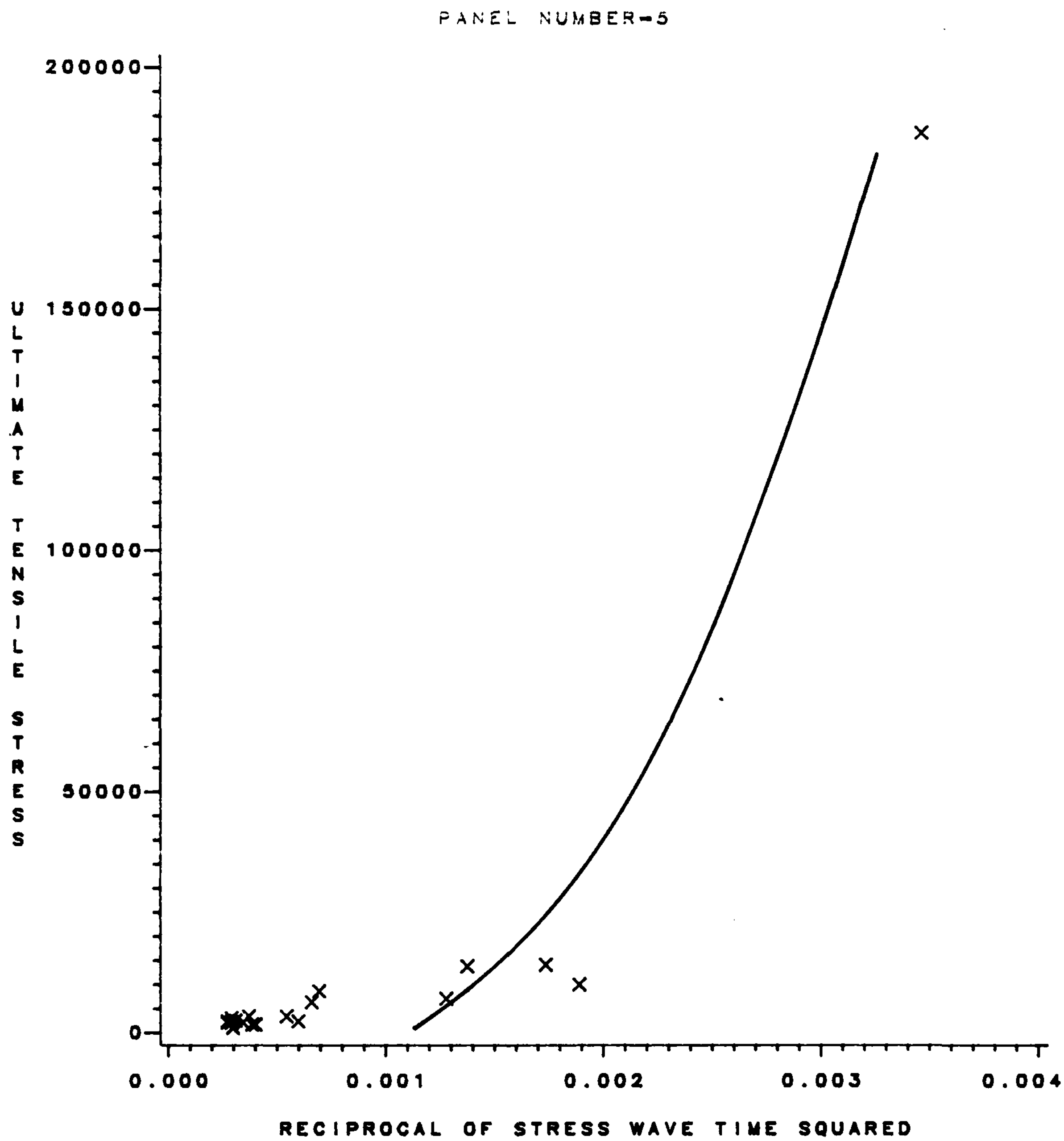


Figure 32. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panel 5.

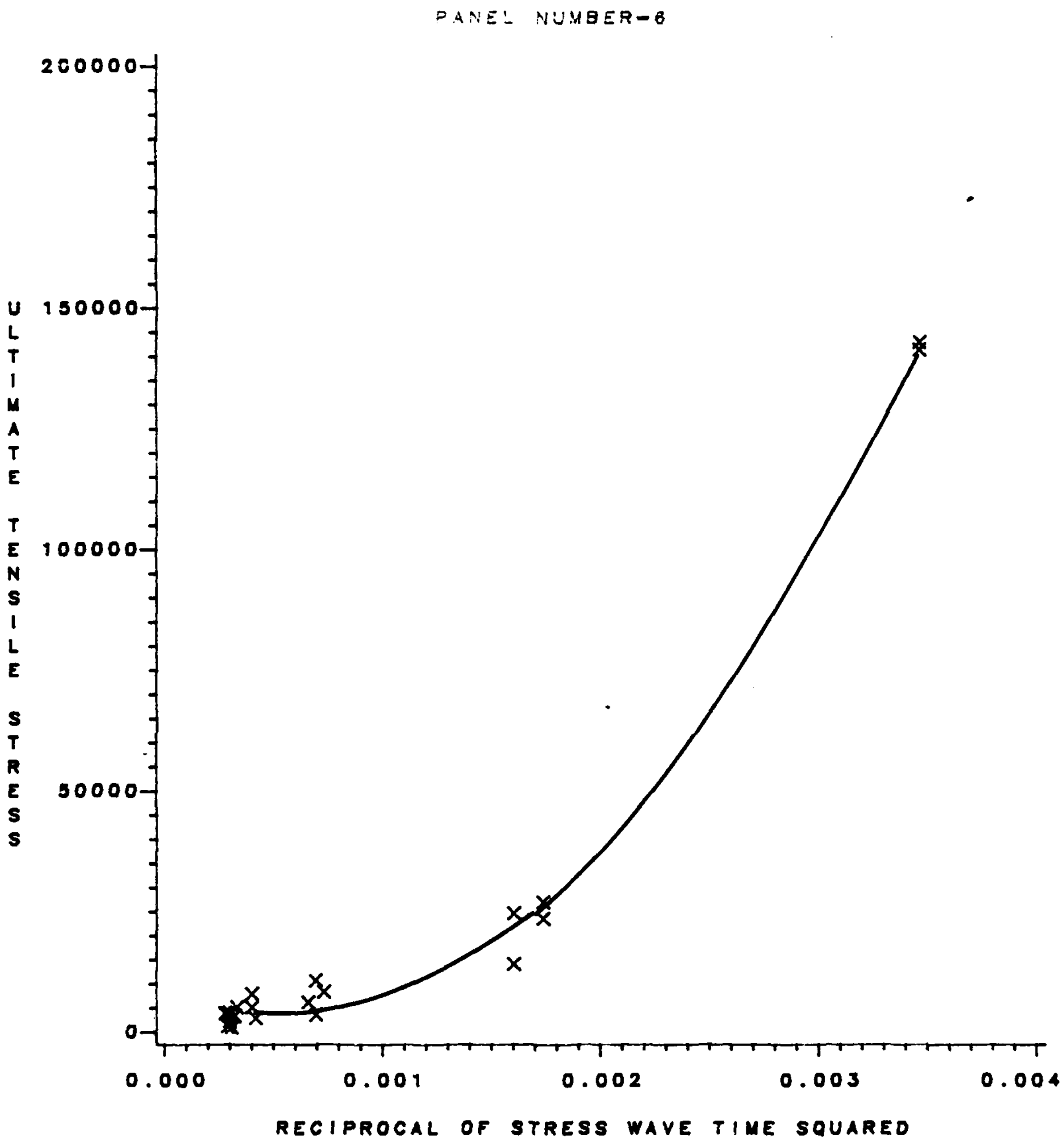


Figure 33. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panel 6.

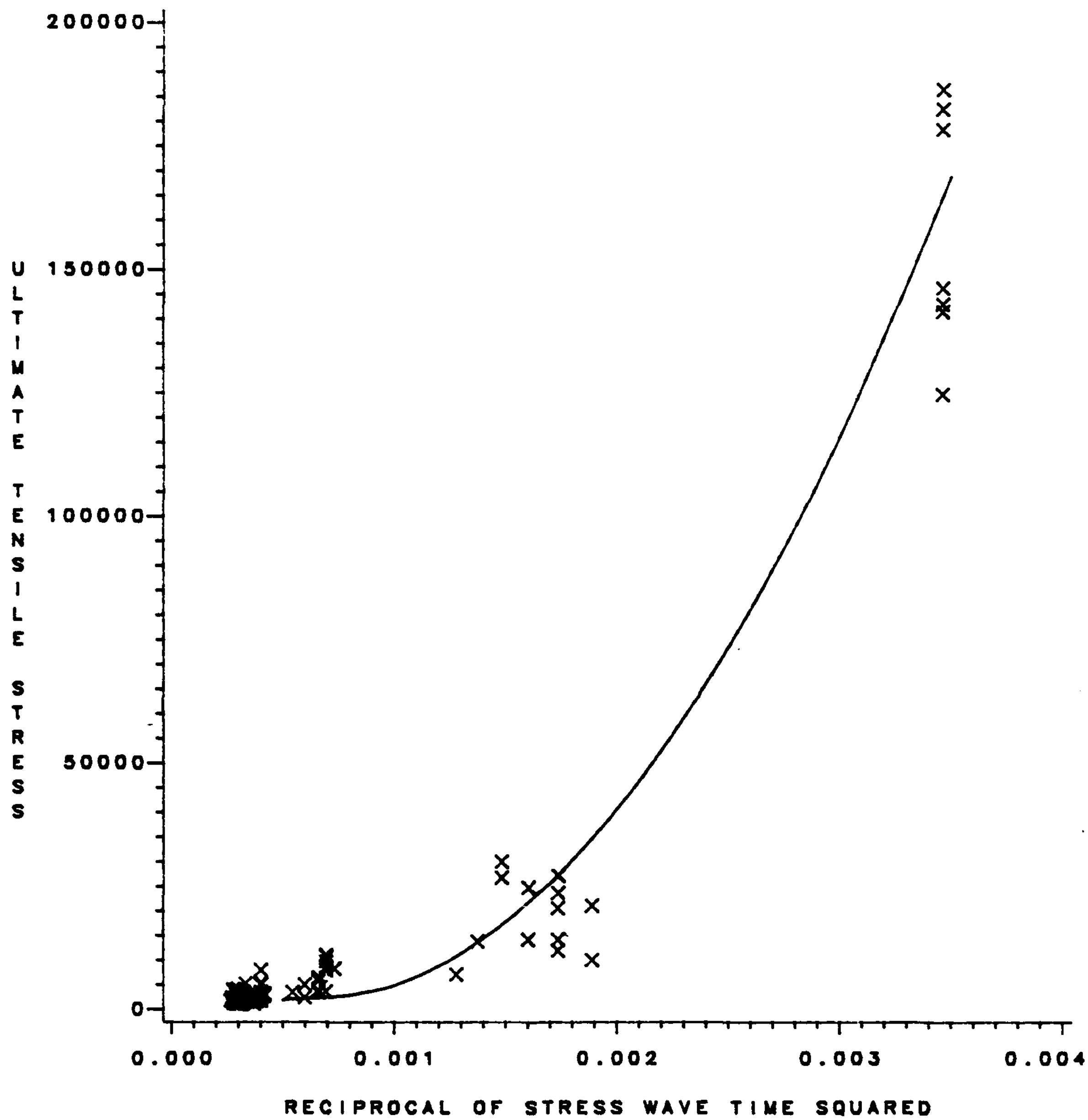


Figure 34. Scatter diagram with regression line for ultimate tensile stress versus reciprocal of stress wave time squared - Panels 1, 3, 5, and 6.

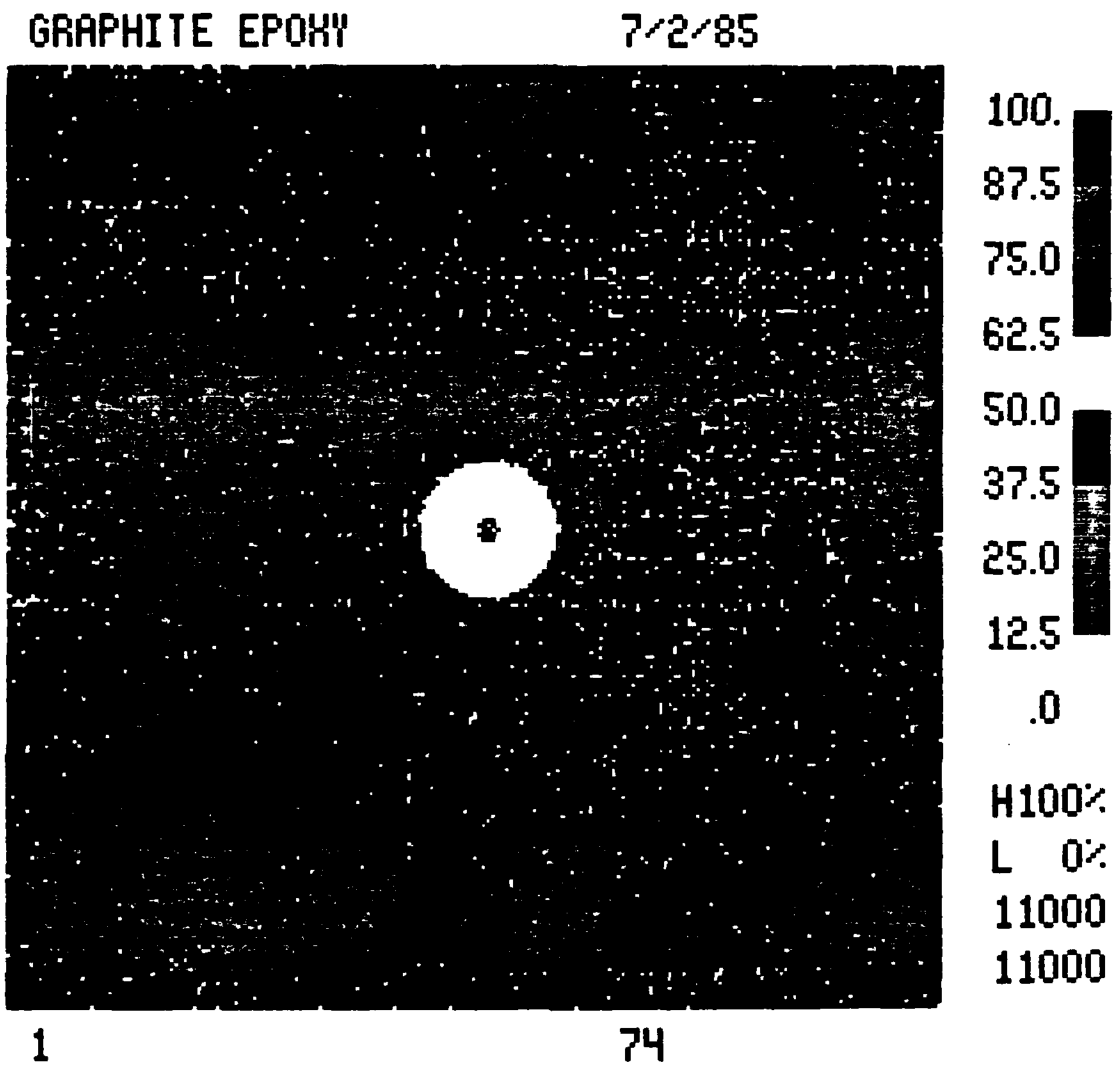


Figure 35. C-scan of Panel 1.

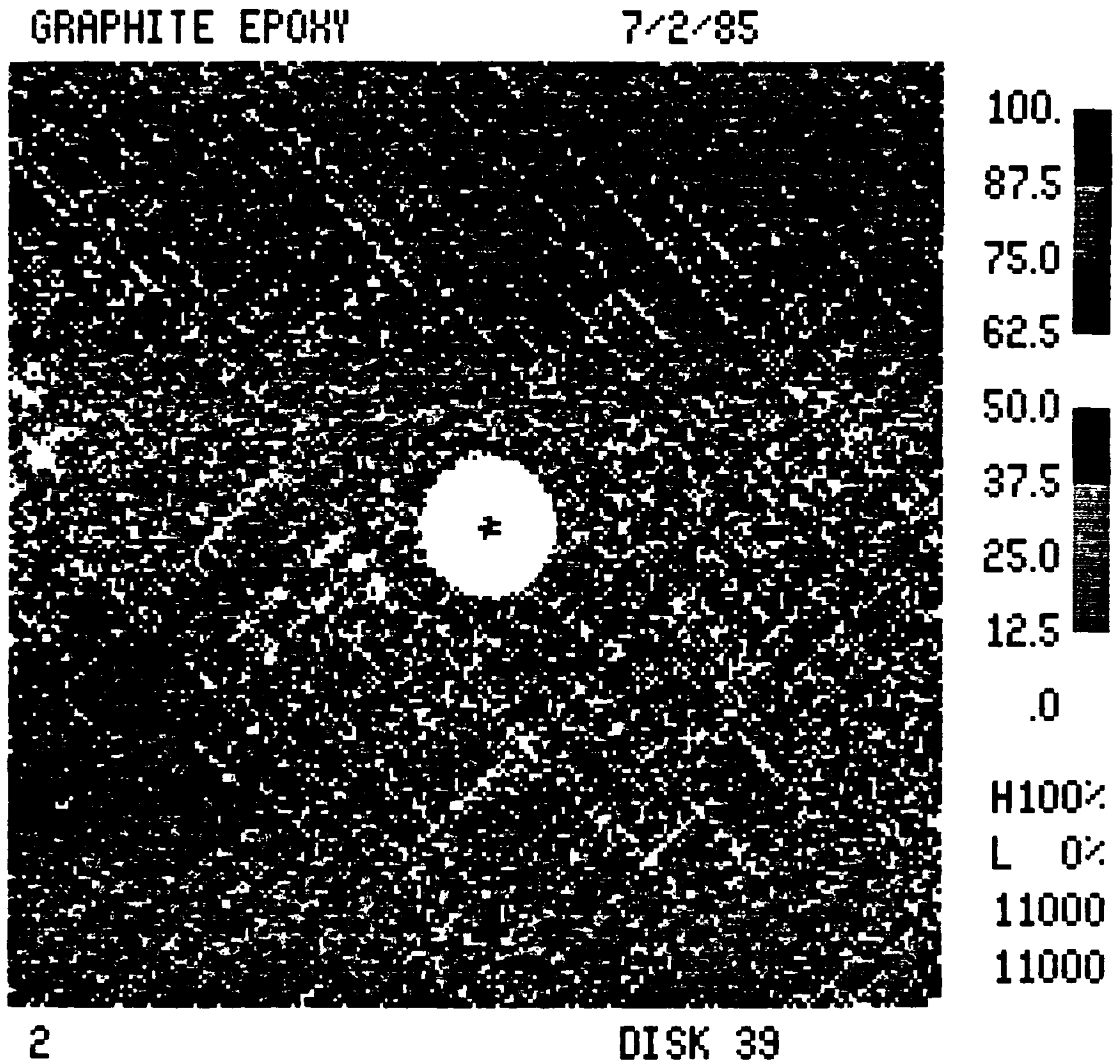


Figure 36. C-scan of Panel 2.

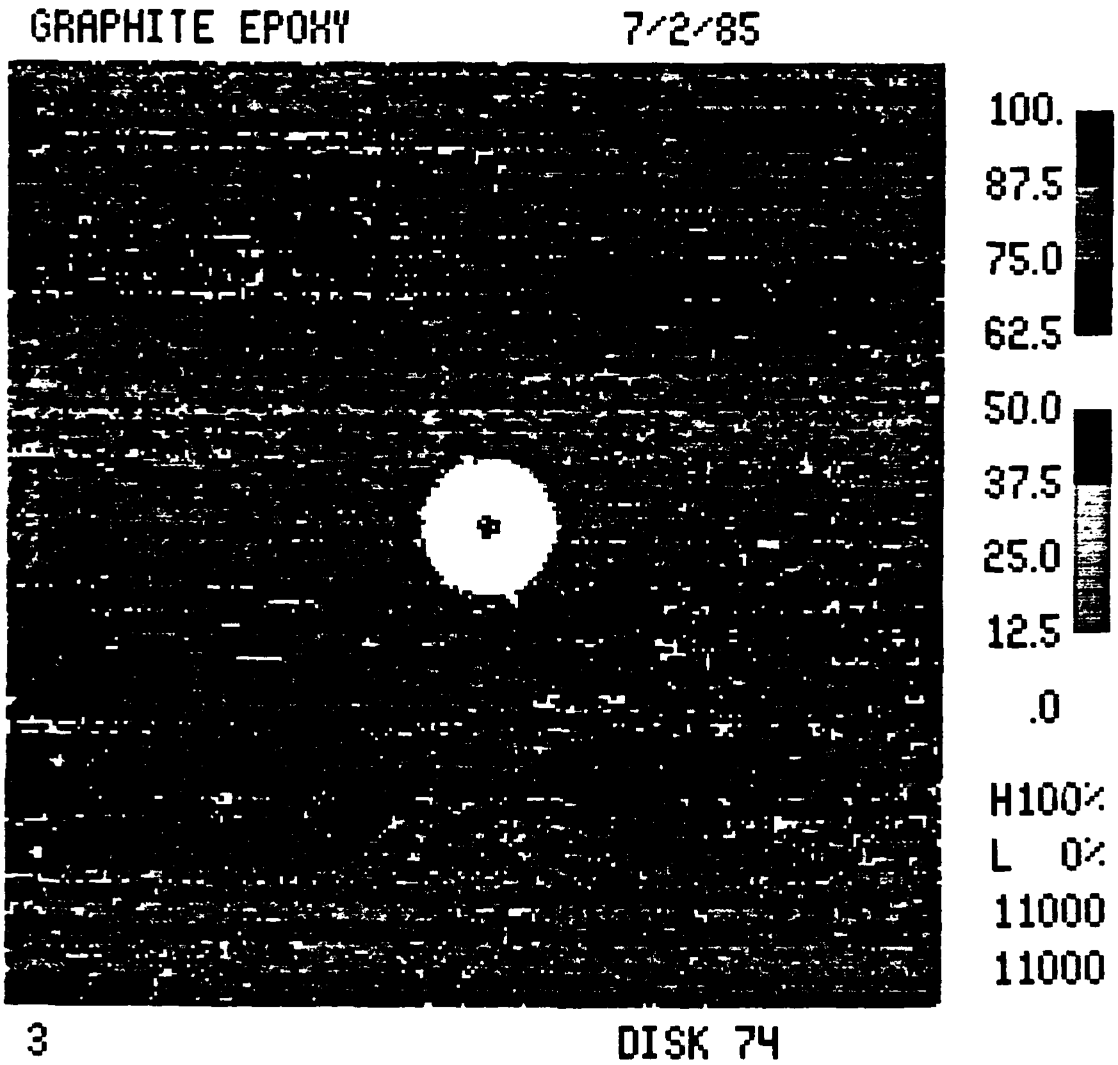


Figure 37. C-scan of Panel 3.

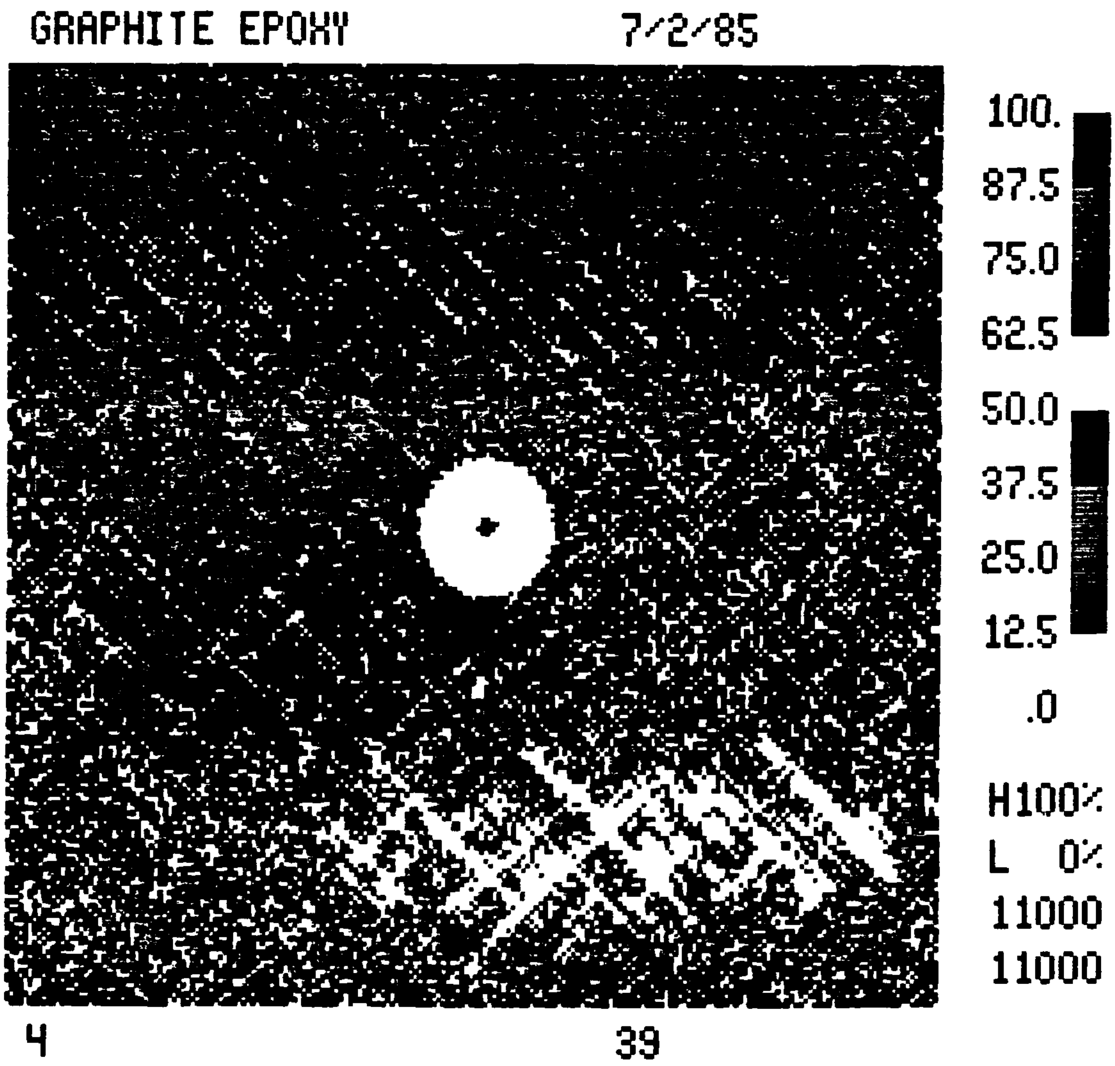


Figure 38. C-scan of Panel 4.

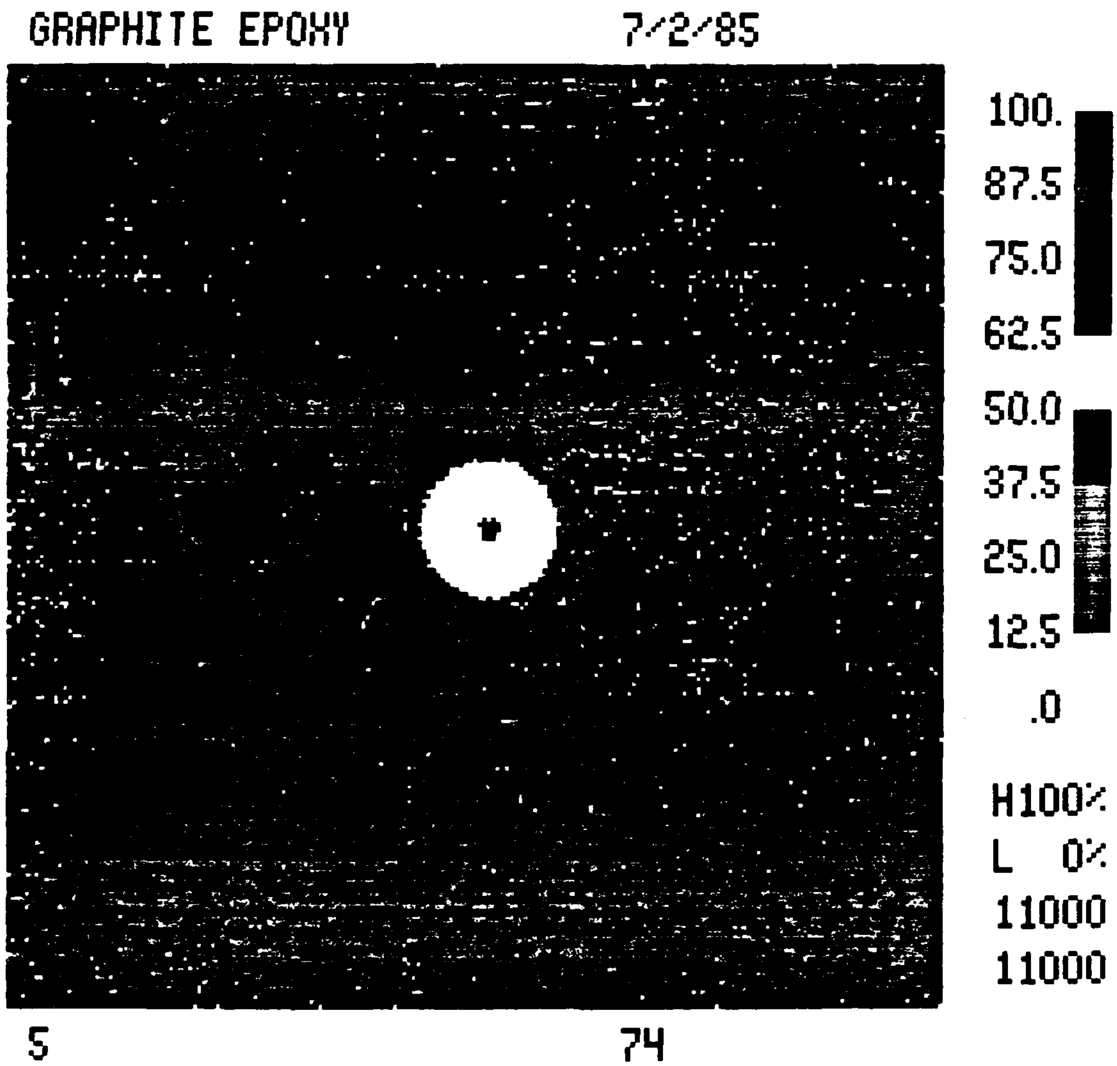


Figure 39. C-scan of Panel 5.

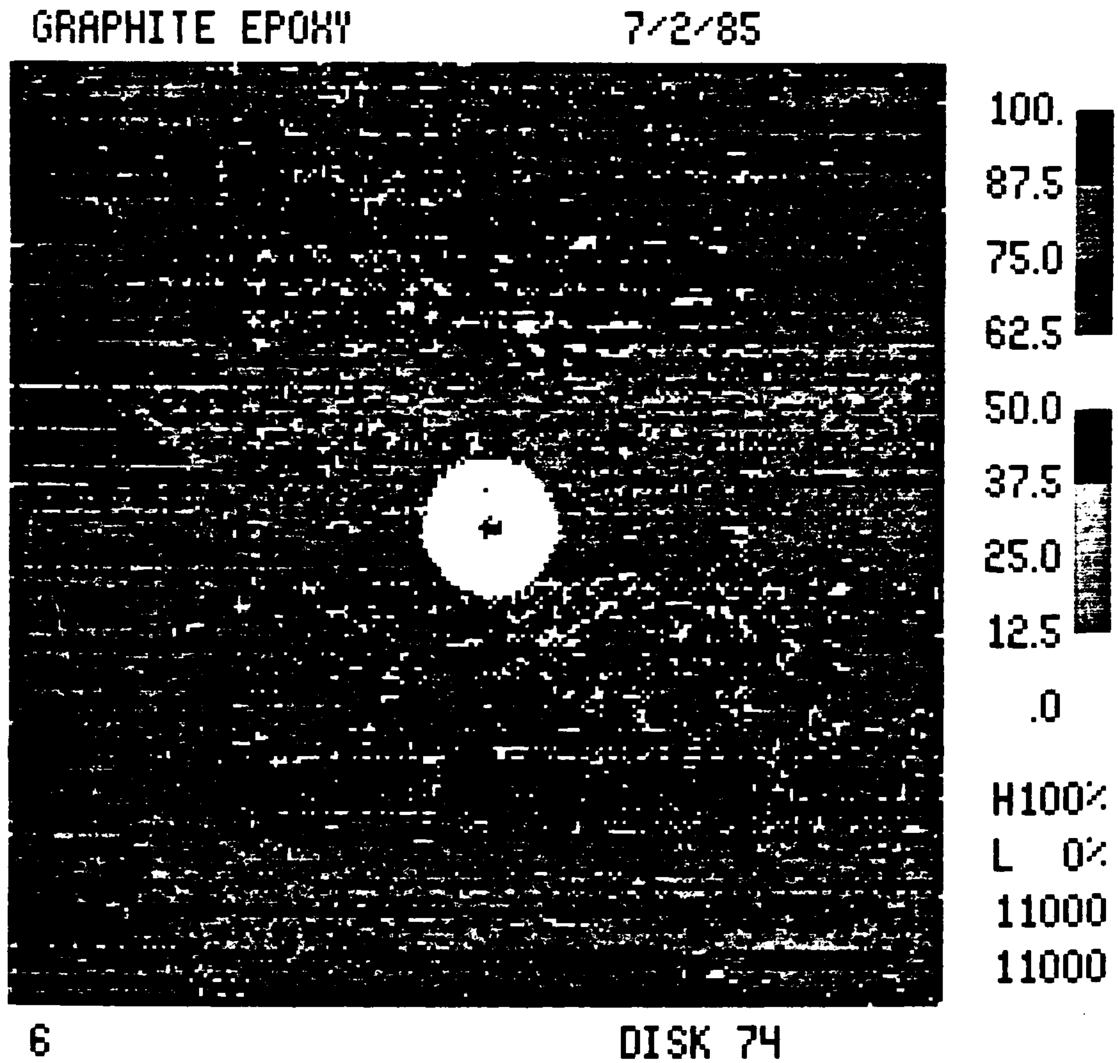


Figure 40. C-scan of Panel 6.

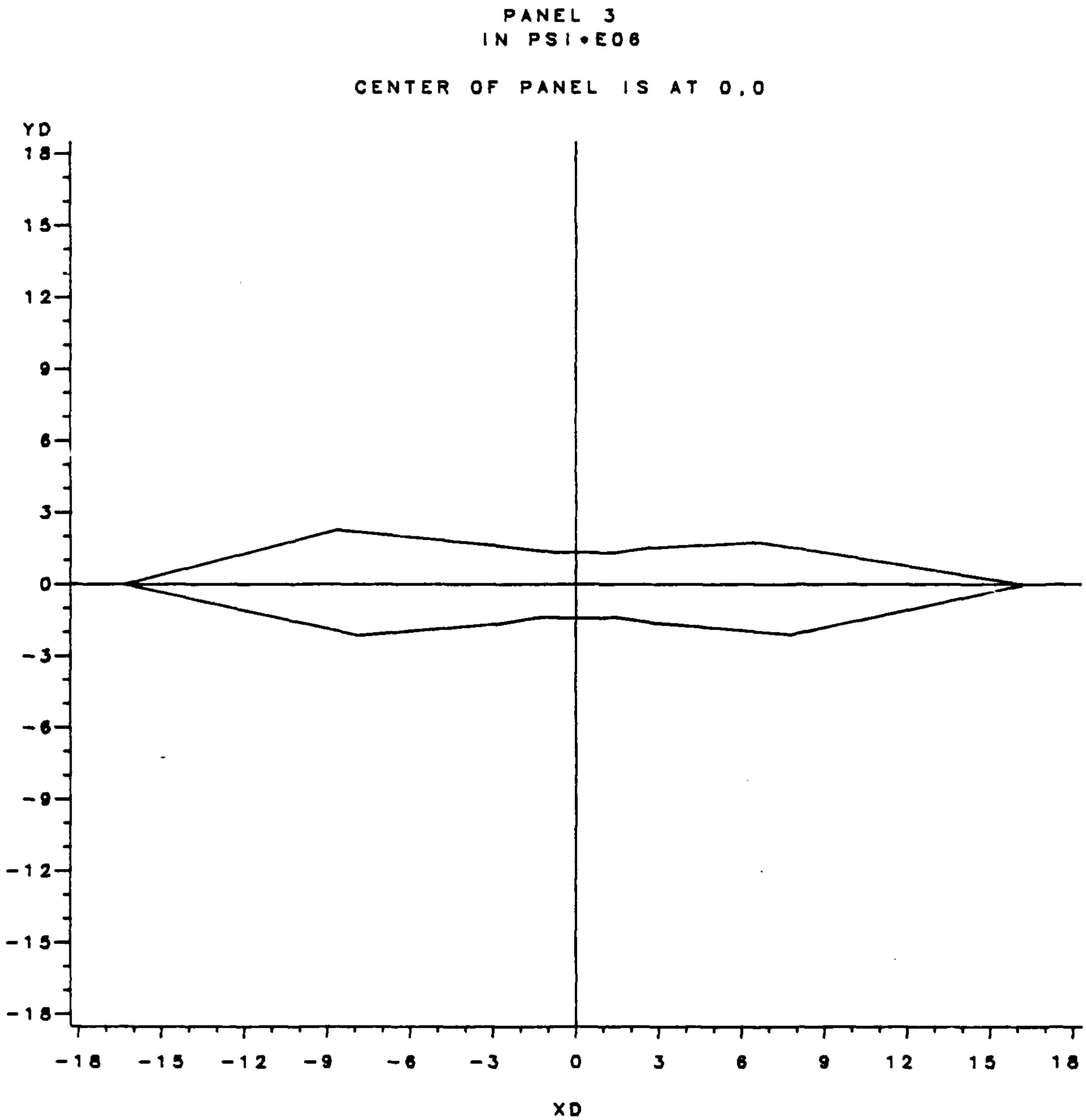


Figure 41. Dynamic MOE distribution of Panel 3.

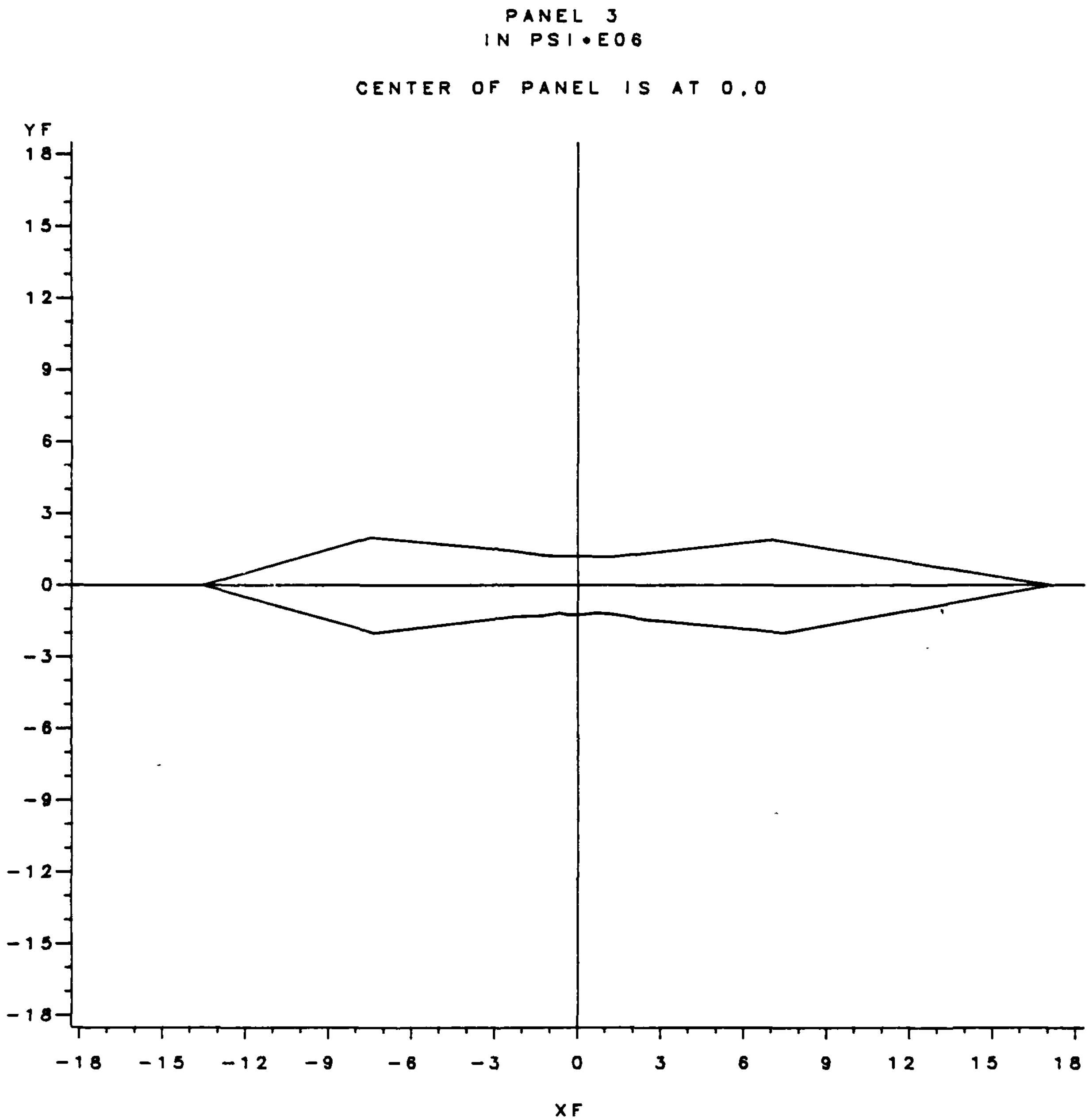


Figure 42. Flexural MOE distribution of Panel 3.

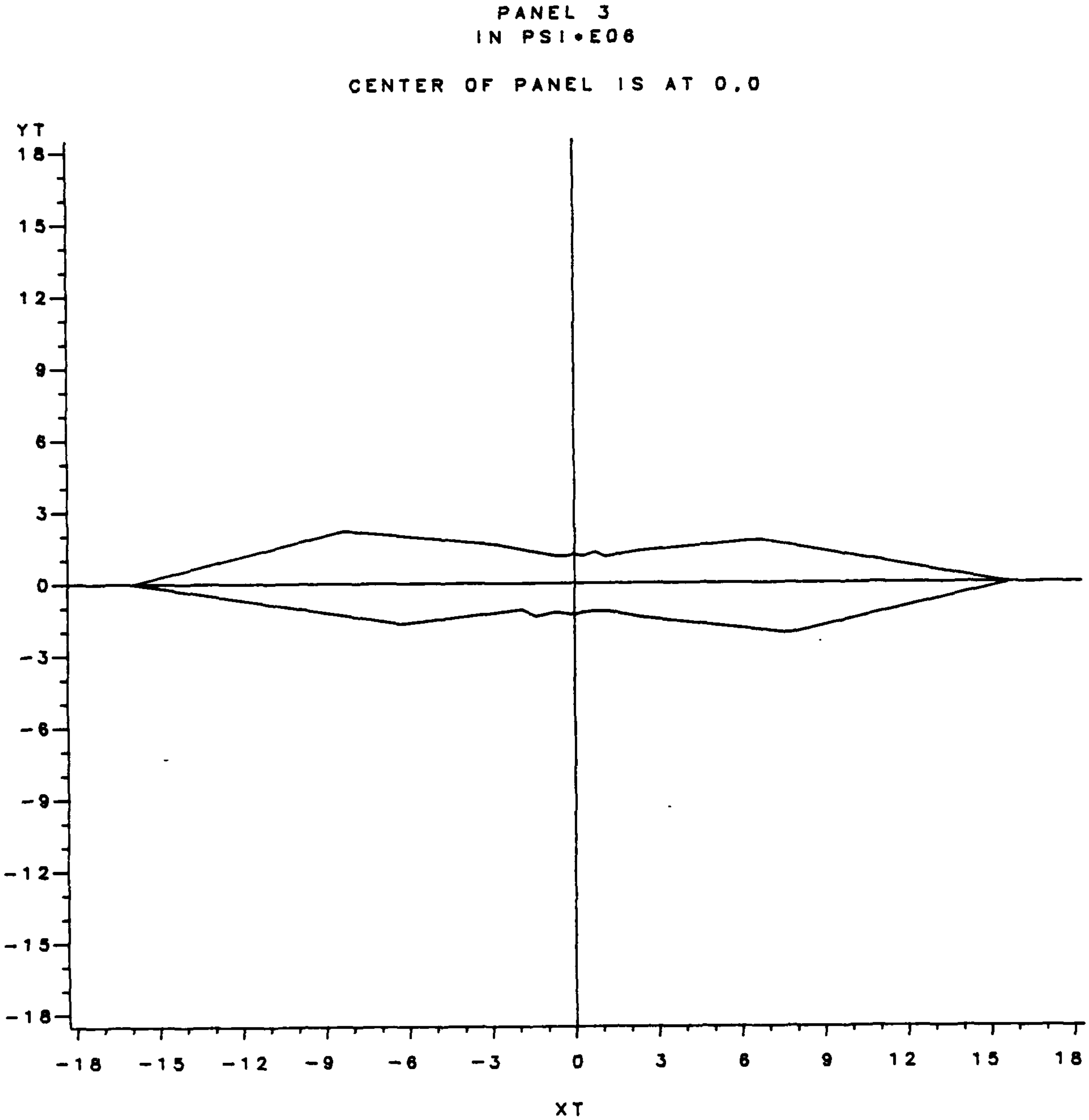


Figure 43. Tensile MOE distribution of Panel 3.

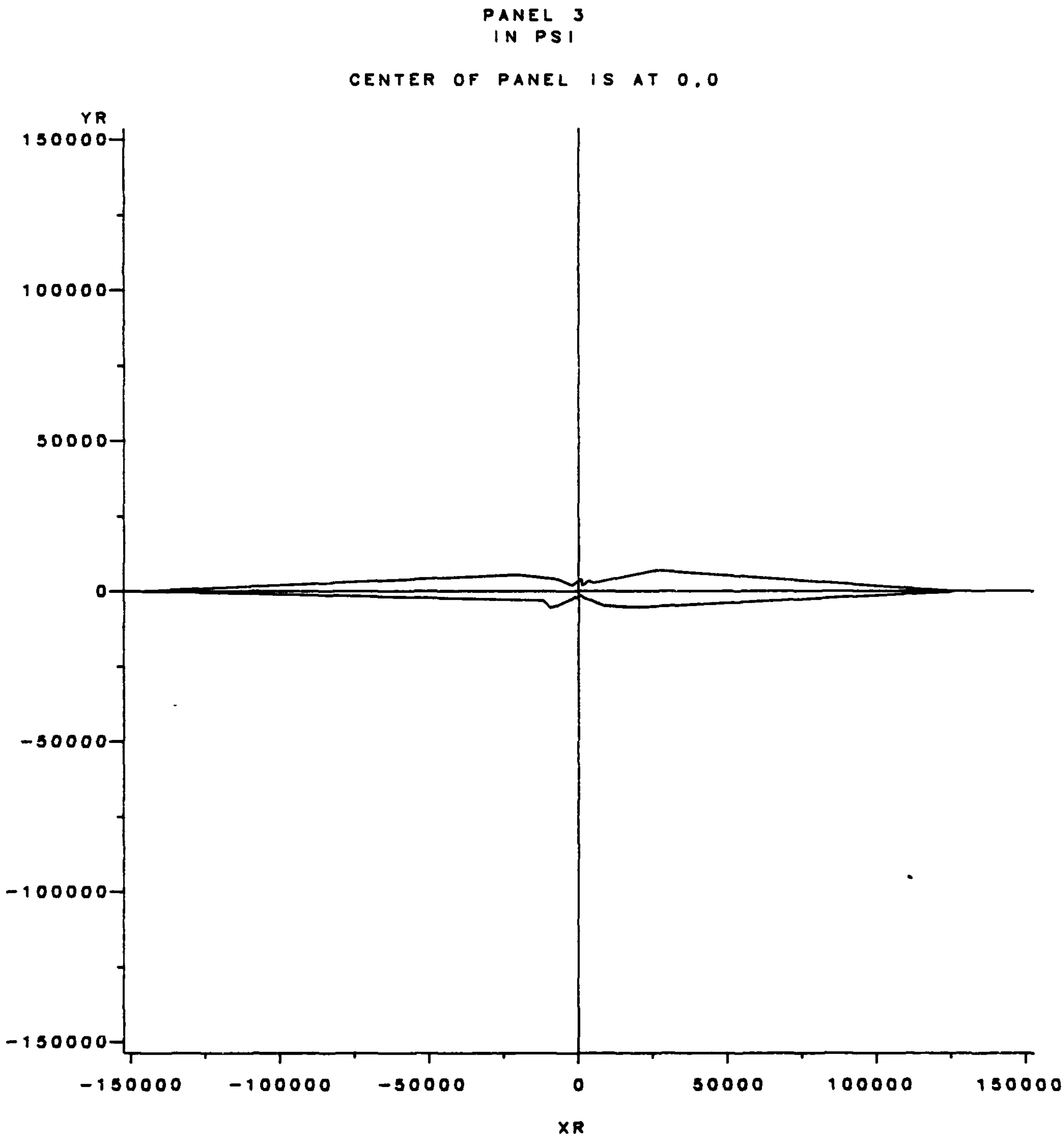


Figure 44. Ultimate tensile stress distribution of Panel 3.

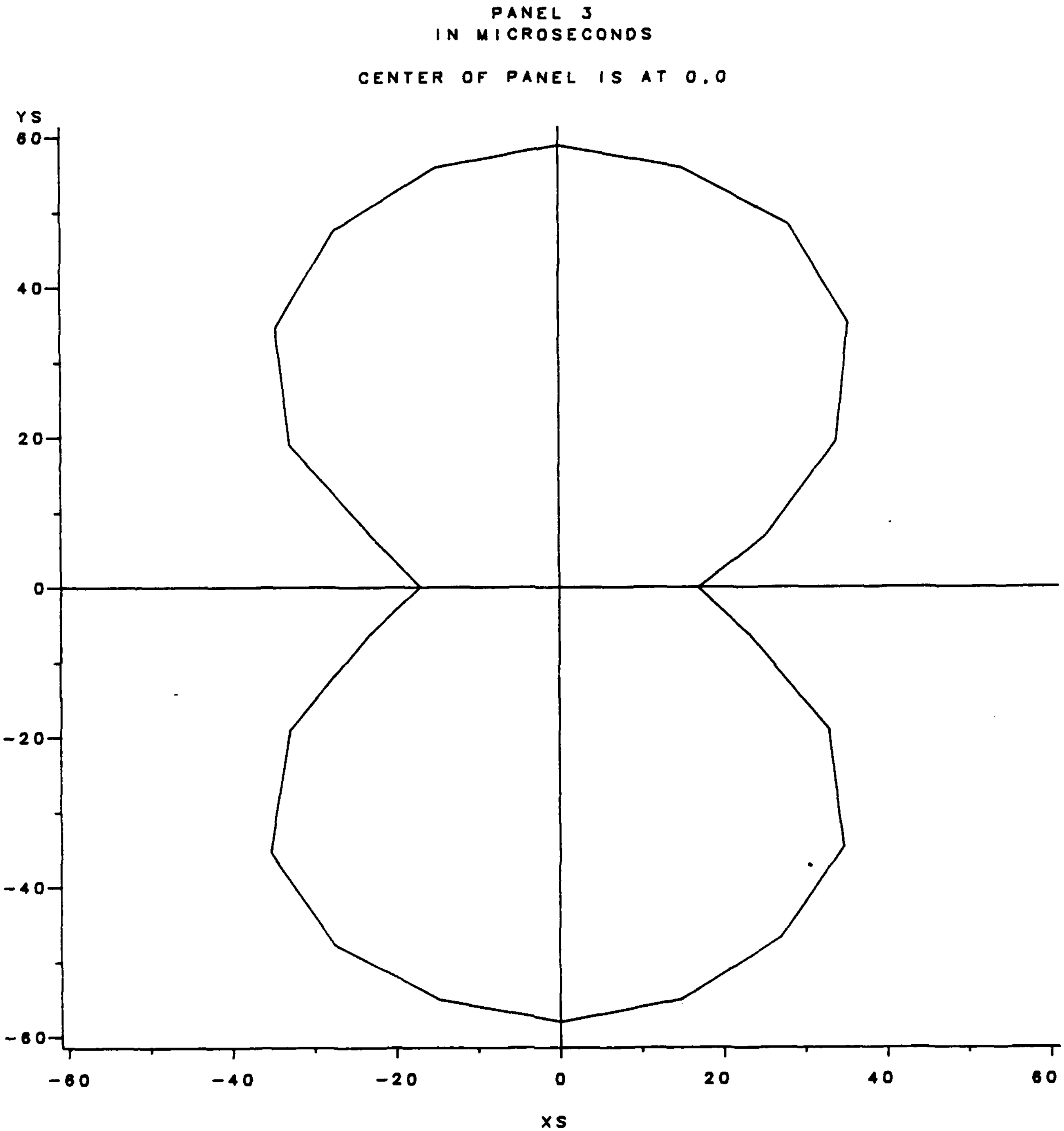


Figure 45. Stress wave time distribution of Panel 3.

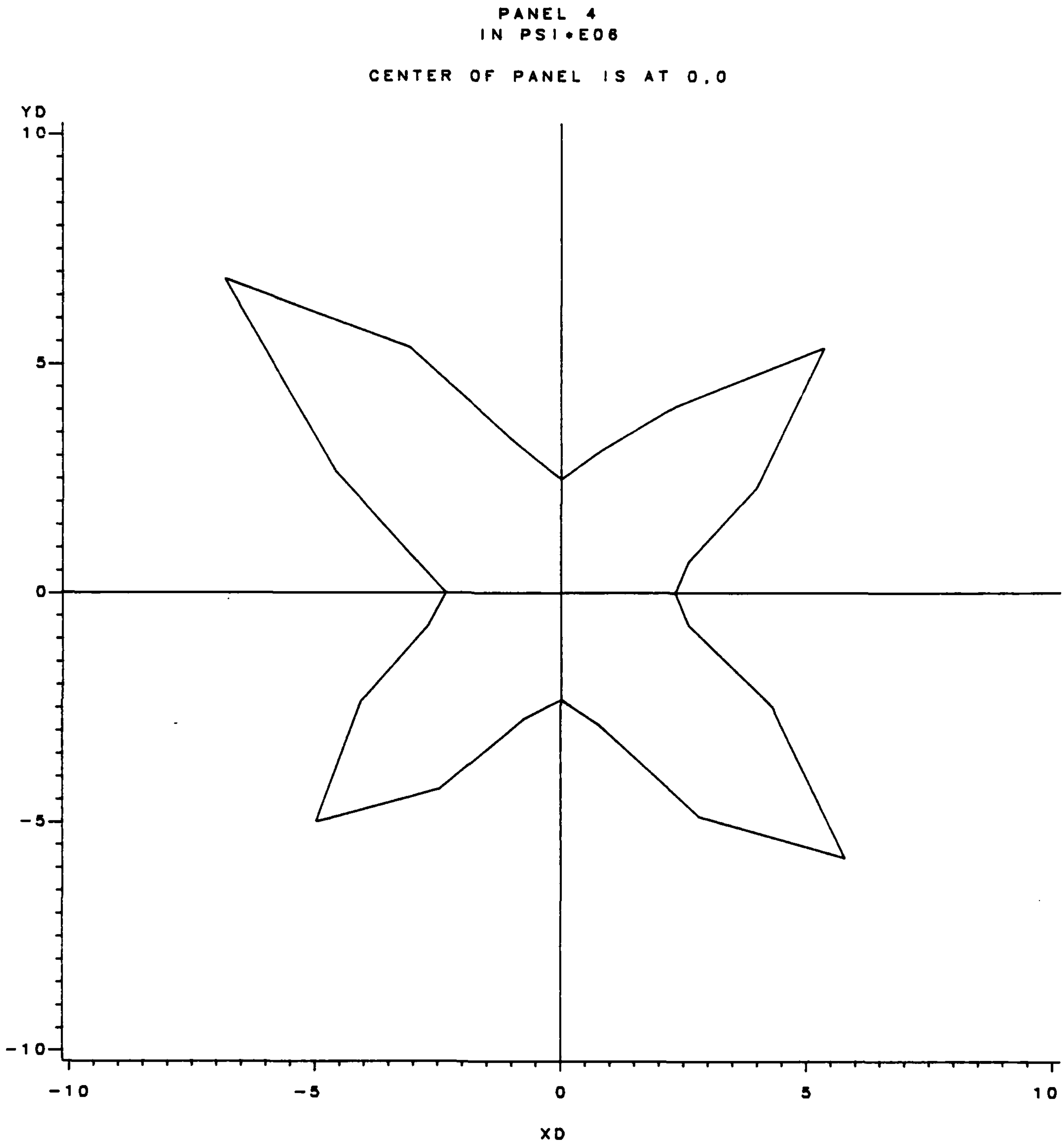


Figure 46. Dynamic MOE distribution of Panel 4.

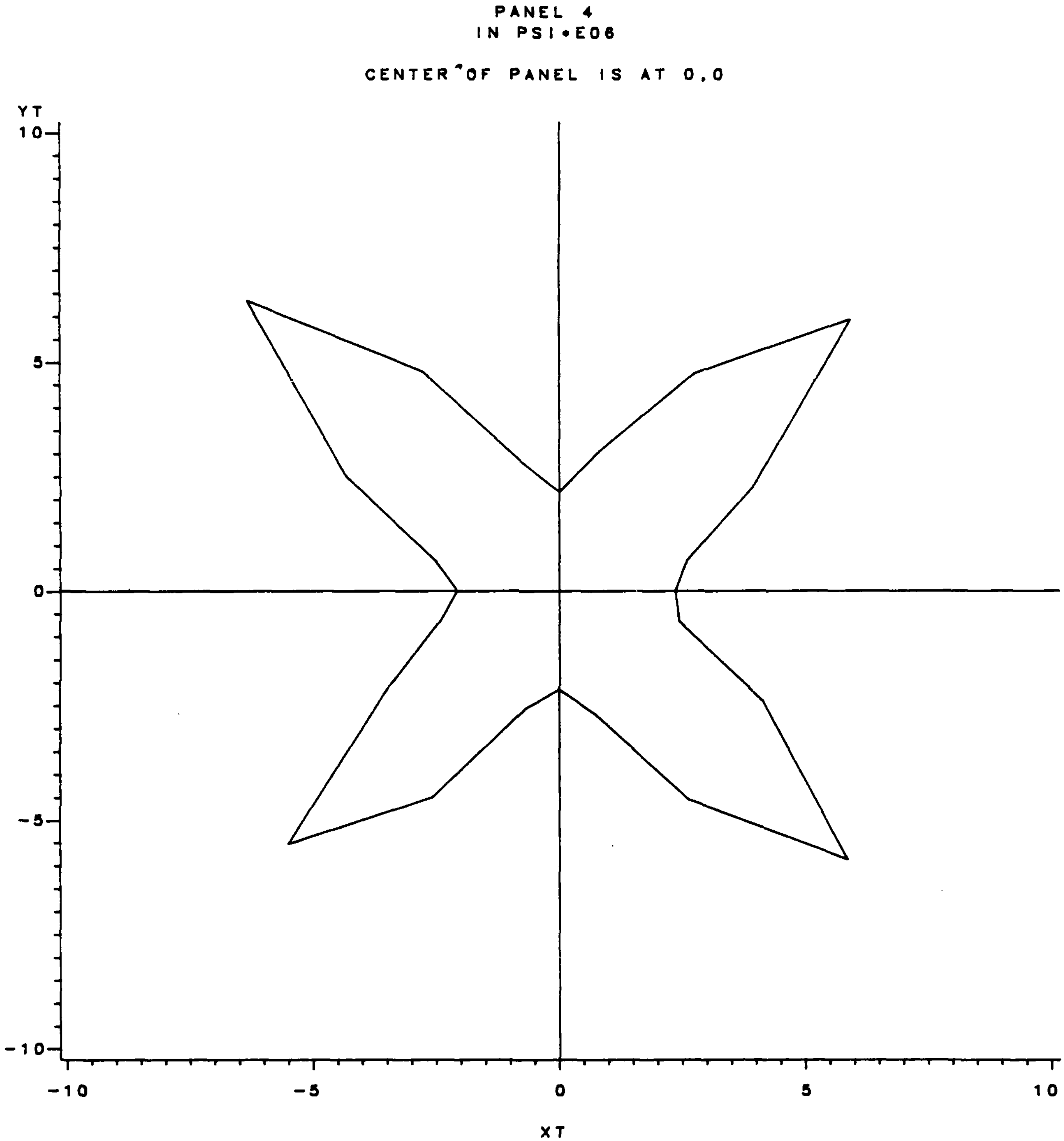


Figure 47. Flexural MOE distribution of Panel 4.

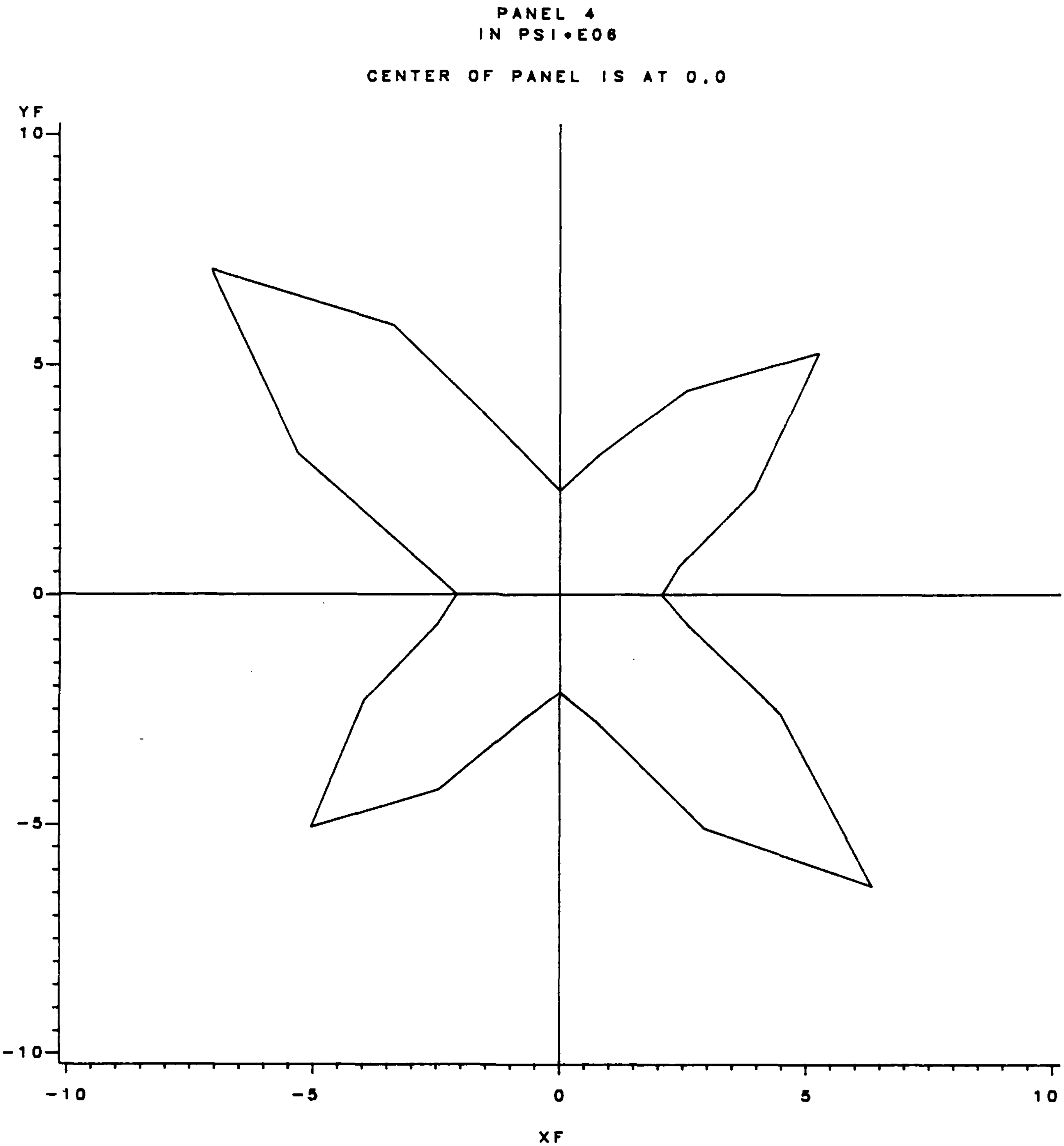


Figure 48. Tensile MOE distribution of Panel 4.

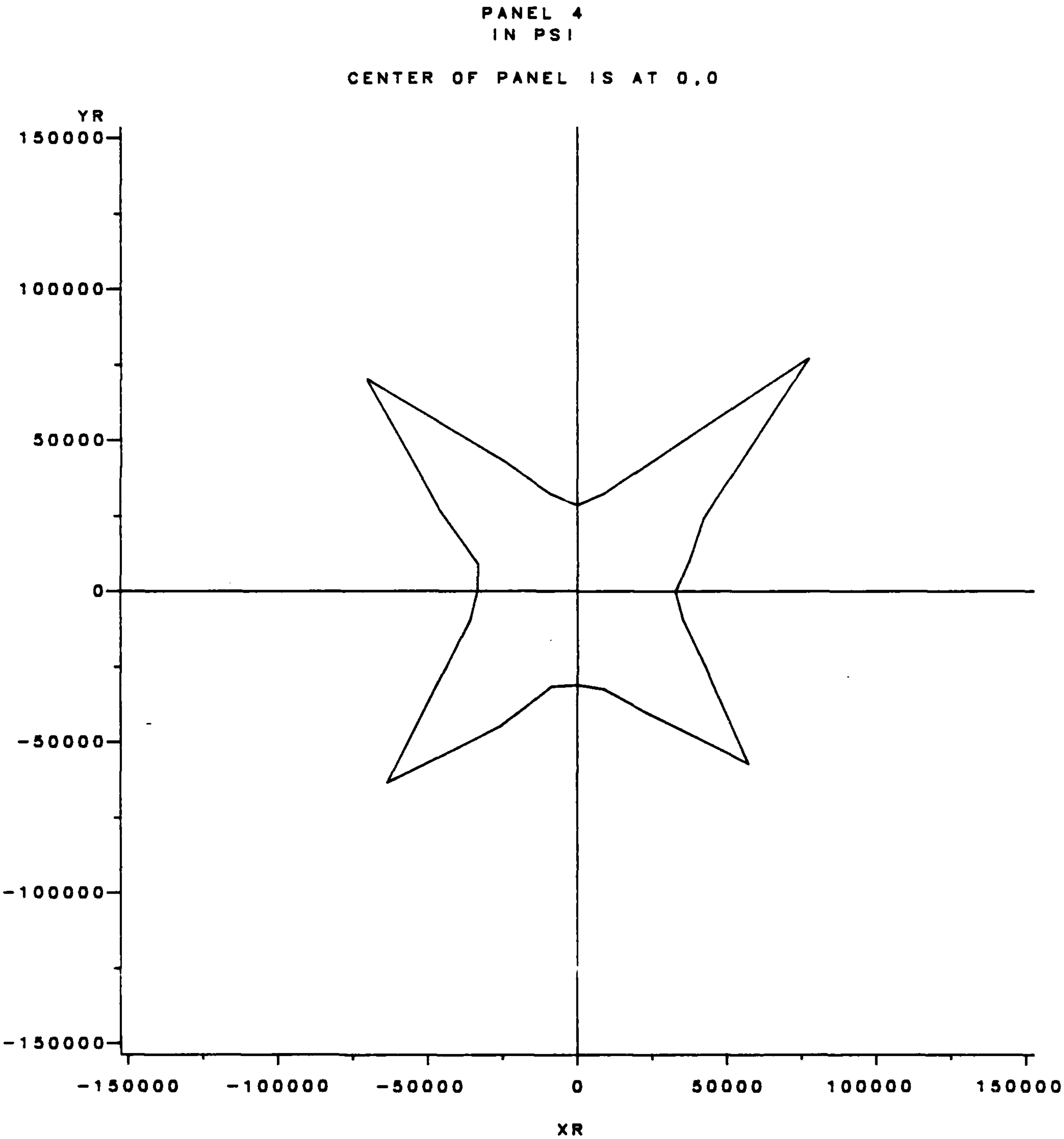


Figure 49. Ultimate tensile stress distribution of Panel 4.

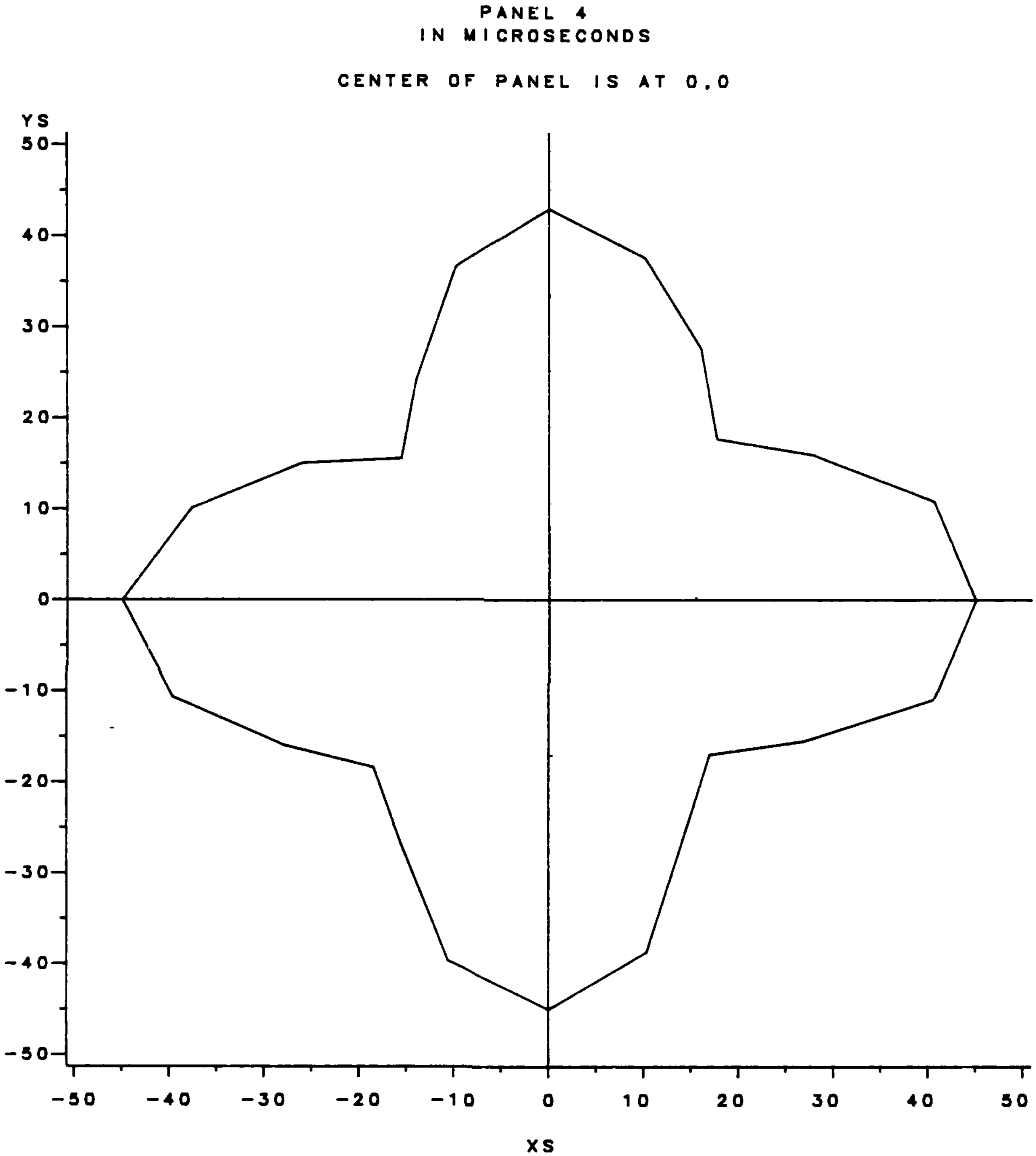


Figure 50. Stress wave time distribution of Panel 4.

Table 1. PROPERTIES OF VARIOUS MATERIALS

Material	Density	Stress Wave Velocity	E
Steel	lb/ft^3	ft/sec	x 10^6 psi
Aluminum	486	16,900	30
Wood (dry Douglas-fir)	168	16,700	10
parallel to grain	20 to 40	13,000 to 20,000	0.7 to 3.5
perpendicular to grain	20 to 40	2,850 to 4,500	0.035 to 0.175
Particle Board	30 to 50	5,500 to 10,000	0.2 to 1.1

Table 2. PROPERTIES OF SPECIMENS 1-0 to 1-345

Specimen Number	Length Inches	Width Inches	Thickness Inches	Weight Grams	Density lbs/cu in	t/ 5.8125	E_d x 10^6 psi	MOE_f x 10^6 psi	MOE_t x 10^6 psi	MOR_t psi
1-0	8.92	0.496	0.0489	5.356	0.0546	17	16.53	14.86	14.72	178,300
1-15	7.12	0.496	0.0489	4.260	0.0544	26	7.04	7.26	7.36	30,100
1-30	8.22	0.496	0.0483	4.885	0.0547	41	2.85	2.98	2.58	5,100
1-45	10.44	0.496	0.0456	5.919	0.0553	52	1.79	2.21	1.75	1,100
1-60	8.19	0.496	0.0461	4.726	0.0556	58	1.45	1.67	1.66	2,100
1-75	7.16	0.496	0.0462	4.183	0.0562	60	1.37	1.58	1.31	1,600
1-90	8.67	0.496	0.0486	5.141	0.0542	62	1.23	1.49	1.08	1,800
1-105	7.22	0.496	0.0471	4.259	0.0557	60	1.35	1.57	1.50	1,650
1-120	8.25	0.496	0.0482	4.816	0.0538	58	1.40	1.55	1.34	1,700
1-135	10.47	0.496	0.0471	5.754	0.0519	52	1.68	1.99	2.16	1,800
1-150	8.22	0.496	0.0464	4.570	0.0533	39	3.06	3.36	3.56	3,800
1-165	7.09	0.496	0.0455	3.940	0.0543	24	8.25	8.11	6.00	Grip
1-180	9.00	0.496	0.0485	5.243	0.0534	17	16.17	15.23	14.85	182,500
1-195	7.19	0.496	0.0442	3.909	0.0547	25	7.66	8.71	7.86	Grip
1-210	8.22	0.496	0.0452	4.547	0.0544	39	3.13	3.34	3.38	3,300
1-225	8.75	0.496	0.0464	4.951	0.0542	52	1.75	2.00	2.03	1,600
1-240	8.22	0.496	0.0472	4.794	0.0549	59	1.38	1.58	*	*
1-255	7.16	0.496	0.0475	4.219	0.0551	60	1.34	1.46	1.29	1,150
1-270	8.66	0.496	0.0471	5.046	0.0550	61	1.29	1.48	1.18	1,800
1-285	7.13	0.496	0.0464	4.068	0.0547	60	1.33	1.47	1.34	1,650
1-300	8.19	0.496	0.0456	4.671	0.0556	57	1.50	1.65	1.36	2,050
1-315	10.38	0.496	0.0447	5.867	0.0562	50	1.97	2.07	2.26	2,500
1-330	8.19	0.496	0.0446	4.607	0.0561	38	3.40	3.27	*	*
1-345	7.12	0.496	0.0465	4.104	0.0551	24	8.37	8.79	*	*

*Extensometer malfunctioned

Table 3. PROPERTIES OF SPECIMENS 2-0 to 2-345

Specimen Number	Length Inches	Width Inches	Thickness Inches	Weight Grams	Density lbs/in^3	t/ 5.8125	E_d $\times 10^6$ psi	MOE_f $\times 10^6$ psi	MOE_t $\times 10^6$ psi	MOR_t psi
2-0	8.66	0.494	0.108	11.401	0.0544	44	2.46	2.15	2.20	31,100
2-15	7.13	0.496	0.110	9.501	0.0539	41	2.81	2.62	2.41	34,450
2-30	8.19	0.495	0.109	10.798	0.0539	32	4.61	4.78	3.86	52,800
2-45	10.44	0.495	0.105	13.462	0.0547	25	7.66	6.77	8.74	98,100
2-60	8.25	0.492	0.102	10.581	0.0563	31	5.13	5.01	5.53	55,300
2-75	7.13	0.494	0.101	9.020	0.0559	39	3.22	2.94	2.75	37,100
2-90	8.70	0.495	0.102	11.088	0.0557	43	2.63	2.34	2.15	32,100
2-105	7.22	0.496	0.099	9.103	0.0566	38	3.43	3.37	2.94	33,850
2-120	8.25	0.492	0.100	10.474	0.0569	28	6.35	6.41	5.71	49,300
2-135	10.50	0.493	0.102	13.413	0.0560	23	9.27	8.90	8.88	98,450
2-150	8.19	0.494	0.106	10.610	0.0546	30	5.31	6.15	5.13	45,350
2-165	7.13	0.492	0.109	9.384	0.0541	40	2.96	2.90	2.66	33,200
2-180	9.20	0.480	0.109	11.751	0.0538	44	2.43	2.10	1.84	27,700
2-195	7.13	0.483	0.108	9.301	0.0552	41	2.87	2.67	2.55	34,100
2-210	8.19	0.494	0.106	10.658	0.0548	32	4.68	4.65	4.15	49,650
2-225	10.38	0.496	0.104	13.471	0.0555	25	7.77	6.86	7.82	105,650
2-240	8.22	0.496	0.103	10.666	0.0560	31	5.10	5.40	5.32	56,750
2-255	7.13	0.497	0.102	9.169	0.0560	40	3.06	3.06	3.01	37,700
2-270	8.63	0.496	0.102	11.072	0.0559	44	2.53	2.37	2.32	30,050
2-285	7.16	0.496	0.103	9.225	0.0556	38	3.37	3.06	3.02	32,900
2-300	8.19	0.496	0.103	10.628	0.0560	28	6.25	6.38	5.76	47,450
2-315	10.38	0.496	0.104	13.555	0.0558	23	9.24	9.60	8.21	89,650
2-330	8.16	0.496	0.106	10.687	0.0549	30	5.34	5.74	4.76	45,650
2-345	7.16	0.490	0.107	9.433	0.0554	40	3.03	2.95	2.65	33,400

Table 4. PROPERTIES OF SPECIMENS 3-0 to 3-345

Specimen Number	Length Inches	Width Inches	Thickness Inches	Weight Grams	Density lbs/in^3	t/ 5.75	E_d $\times 10^6$ psi	MOE_f $\times 10^6$ psi	MOE_t $\times 10^6$ psi	MOR_t psi
3-0	8.91	0.495	0.1620	17.685	0.0546	17	16.18	16.97	15.59	124,700
3-15	7.13	0.496	0.1614	14.067	0.0544	26	6.89	7.34	6.94	26,850
3-30	8.22	0.488	0.1602	15.839	0.0543	39	3.06	2.67	2.71	5,850
3-45	10.41	0.499	0.1598	20.588	0.0547	50	1.87	1.70	1.57	5,100
3-60	8.25	0.498	0.1576	16.444	0.0560	56	1.53	1.36	1.52	2,250
3-75	7.16	0.497	0.1554	13.981	0.0558	58	1.42	1.28	1.18	4,200
3-90	8.69	0.492	0.1551	16.676	0.0555	59	1.36	1.22	1.21	3,450
3-105	7.16	0.490	0.1535	13.602	0.0557	58	1.42	1.28	1.21	3,100
3-120	8.25	0.488	0.1530	15.635	0.0560	55	1.58	1.40	1.33	3,050
3-135	10.44	0.490	0.1536	19.942	0.0560	49	2.00	1.76	1.81	2,900
3-150	8.16	0.492	0.1558	15.612	0.0551	38	3.27	2.91	3.26	8,100
3-165	7.13	0.494	0.1588	13.932	0.0550	23	8.90	7.74	8.61	21,150
3-180	9.00	0.493	0.1588	17.634	0.0552	17	16.35	13.57	15.97	146,250
3-195	7.13	0.492	0.1569	13.726	0.0550	24	8.18	7.62	6.48	12,050
3-210	8.19	0.492	0.1561	15.841	0.0555	38	3.29	2.60	2.17	11,050
3-225	10.38	0.498	0.1552	20.263	0.0557	50	1.91	1.79	1.95	3,500
3-240	8.19	0.499	0.1559	16.010	0.0554	55	1.57	1.34	1.36	2,250
3-255	7.09	0.497	0.1562	13.808	0.0553	57	1.46	1.27	-	-
3-270	8.69	0.491	0.1577	16.695	0.0547	58	1.39	1.21	1.29	2,000
3-285	7.13	0.489	0.1594	13.866	0.0550	57	1.45	1.24	1.23	1,500
3-300	8.19	0.483	0.1622	15.957	0.0548	54	1.61	1.32	1.35	1,600
3-315	10.41	0.485	0.1630	20.245	0.0543	49	1.94	1.70	1.64	3,200
3-330	8.19	0.488	0.1624	16.049	0.0545	38	3.23	2.85	2.87	9,700
3-345	7.13	0.491	0.1625	13.994	0.0543	24	8.07	7.70	8.03	20,550

Table 5. PROPERTIES OF SPECIMENS 4-0 to 4-345

Specimen Number	Length Inches	Width Inches	Thickness Inches	Weight Grams	Density lbs/in^3	t/ 5.8125	E_d $\times 10^6$ psi	MOE_f $\times 10^6$ psi	MOE_t $\times 10^6$ psi	MOR_t $\times 10^6$ psi
4-0	9.00	0.495	0.1103	12.026	0.0539	45	2.33	2.08	2.35	32,800
4-15	7.16	0.491	0.1095	9.507	0.0545	42	2.70	2.53	2.70	38,600
4-30	8.25	0.494	0.1082	10.752	0.0538	32	4.59	4.55	4.54	48,850
4-45	10.56	0.494	0.1006	12.880	0.0541	25	7.57	7.43	8.38	109,650
4-60	8.28	0.493	0.0972	9.944	0.0552	32	4.72	5.14	5.49	49,550
4-75	7.25	0.491	0.0945	8.559	0.0561	39	3.23	3.18	3.17	33,400
4-90	8.78	0.494	0.1028	10.596	0.0524	43	2.48	2.27	2.17	28,350
4-105	7.22	0.492	0.0939	8.367	0.0553	38	3.35	3.35	2.93	33,350
4-120	8.28	0.492	0.0963	9.866	0.0554	28	6.19	6.77	5.55	50,100
4-135	10.41	0.493	0.1008	12.580	0.0536	22	9.70	10.01	8.98	99,800
4-150	8.13	0.493	0.1067	10.522	0.0543	30	5.28	6.13	5.00	52,750
4-165	7.06	0.493	0.1082	9.284	0.0543	39	3.13	2.98	2.60	34,500
4-180	8.91	0.492	0.1101	11.861	0.0542	45	2.34	2.09	2.07	33,400
4-195	7.13	0.492	0.1107	9.498	0.0540	41	2.81	2.59	2.51	37,200
4-210	8.13	0.494	0.1091	10.867	0.0547	32	4.68	4.56	3.93	50,850
4-225	10.38	0.495	0.1081	13.738	0.0546	26	7.06	7.14	7.79	89,700
4-240	8.22	0.495	0.1081	10.815	0.0542	31	4.94	4.90	5.19	51,850
4-255	7.19	0.492	0.1075	9.384	0.0544	41	2.83	2.80	2.63	32,500
4-270	8.65	0.491	0.1089	11.327	0.0540	45	2.33	2.12	2.14	30,850
4-285	7.19	0.494	0.1080	9.413	0.0541	40	2.96	2.85	2.76	33,550
4-300	8.25	0.493	0.110	10.996	0.0542	29	5.64	5.87	5.24	46,550
4-315	10.47	0.495	0.1111	14.036	0.0538	24	8.17	8.97	8.27	80,750
4-330	8.22	0.492	0.1119	11.155	0.0544	31	4.95	5.18	4.78	49,050
4-345	7.16	0.493	0.1123	9.691	0.0539	42	2.68	2.72	2.51	36,600

Table 6. PROPERTIES OF SPECIMENS 5-0 to 5-345

Specimen Number	Length Inches	Width Inches	Thickness Inches	Weight Grams	Density lbs/in^3	t/ 5.8125	E_d $\times 10^6$ psi	MOE_f $\times 10^6$ psi	MOE_t $\times 10^6$ psi	MOR_t psi
5-0	8.94	0.510	0.0489	5.590	0.0553	17	16.75	15.53	16.43	186,450
5-15	7.09	0.497	0.0501	4.360	0.0544	27	6.53	8.00	7.17	13,900
5-30	8.19	0.496	0.0485	4.878	0.0546	43	2.58	2.93	2.14	3,450
5-45	10.44	0.497	0.0463	6.078	0.0558	54	1.67	2.03	1.91	2,250
5-60	8.22	0.497	0.0450	4.643	0.0557	59	1.40	1.61	1.26	3,150
5-75	7.16	0.496	0.0446	3.967	0.0552	61	1.30	1.54	1.23	2,100
5-90	8.69	0.495	0.0456	4.866	0.0547	61	1.29	1.44	1.22	2,450
5-105	7.22	0.494	0.0443	3.995	0.0557	59	1.40	1.55	1.22	2,300
5-120	8.28	0.493	0.0443	4.581	0.0558	58	1.45	1.63	1.41	1,350
5-135	10.44	0.494	0.0443	5.771	0.0557	50	1.95	2.10	1.99	1,800
5-150	8.19	0.494	0.0457	4.674	0.0557	38	3.38	3.35	2.89	8,750
5-165	7.13	0.494	0.0468	4.132	0.0553	23	9.15	8.37	7.21	10,100
5-180	8.99	0.493	0.0455	5.212	0.0570	18	15.40	16.82	16.39	204,000
5-195	7.13	0.497	0.0443	3.956	0.0556	28	6.21	7.93	4.73	7,200
5-210	8.22	0.497	0.0433	4.464	0.0556	41	2.89	3.35	3.10	2,500
5-225	10.47	0.497	0.0431	5.736	0.0564	52	1.83	2.13	1.64	3,500
5-240	8.22	0.497	0.0428	4.512	0.0569	58	1.48	1.78	1.45	1,050
5-255	7.18	0.496	0.0435	3.942	0.0561	59	1.41	1.59	-	-
5-270	8.69	0.495	0.0436	4.816	0.0566	61	1.33	1.52	-	-
5-285	7.19	0.493	0.0447	4.017	0.0559	59	1.41	1.51	1.38	2,150
5-300	8.25	0.494	0.0448	4.674	0.0564	57	1.52	1.67	1.39	2,700
5-315	10.44	0.493	0.0463	5.963	0.0552	51	1.86	1.91	2.11	1,850
5-330	8.19	0.494	0.0469	4.712	0.0547	39	3.15	3.14	2.51	6,500
5-345	7.09	0.495	0.0492	4.180	0.0533	24	8.10	7.64	6.84	14,200

Table 7. PROPERTIES OF SPECIMENS 6-0 to 6-345

Specimen Number	Length Inches	Width Inches	Thickness Inches	Weight Grams	Density lbs/in^3	t/ 5.75	E_d $\times 10^6$ psi	MOE_f $\times 10^6$ psi	MOE_t $\times 10^6$ psi	MOR_t psi
6-0	8.94	0.492	0.1555	16.564	0.0534	17	15.83	14.48	14.85	143,100
6-15	7.19	0.495	0.1481	13.058	0.0546	24	8.12	8.13	5.68	23,750
6-30	8.25	0.494	0.1518	15.000	0.0535	38	3.17	3.01	2.90	3,700
6-45	10.44	0.496	0.1500	18.993	0.0539	49	1.92	1.93	1.84	2,950
6-60	8.19	0.497	0.1568	15.762	0.0544	56	1.49	1.33	1.28	3,550
6-75	7.16	0.494	0.1603	14.107	0.0549	57	1.45	1.25	1.17	1,050
6-90	8.71	0.494	0.1624	17.206	0.0543	59	1.34	1.21	-	1,300
6-105	7.22	0.490	0.1598	14.100	0.0550	58	1.40	1.26	1.20	2,400
6-120	8.19	0.487	0.158	15.852	0.0554	56	1.51	1.34	1.30	3,550
6-135	10.44	0.490	0.1562	19.975	0.0551	50	1.89	1.79	1.68	5,300
6-150	8.22	0.491	0.1558	15.827	0.0555	39	3.13	2.89	2.51	6,300
6-165	7.13	0.491	0.1569	13.818	0.0555	25	7.61	7.63	7.21	24,750
6-180	8.97	0.503	0.1602	18.164	0.0554	17	16.42	15.24	15.51	141,500
6-195	7.16	0.494	0.1585	14.145	0.0556	24	8.27	7.78	7.98	27,150
6-210	8.16	0.496	0.1553	16.002	0.0561	37	3.51	2.88	2.50	8,300
6-225	10.41	0.498	0.1547	20.322	0.0559	50	1.92	1.74	1.71	8,000
6-240	8.22	0.497	0.1564	16.228	0.0560	55	1.59	1.36	1.31	5,250
6-255	7.16	0.495	0.1582	14.107	0.0555	58	1.41	1.24	1.24	3,650
6-270	8.66	0.494	0.160	17.128	0.0552	60	1.31	1.21	1.27	3,900
6-285	7.16	0.490	0.1595	14.058	0.0554	60	1.32	1.25	1.21	4,000
6-300	8.25	0.488	0.156	15.850	0.0556	58	1.42	1.38	1.43	4,100
6-315	10.46	0.488	0.1513	18.797	0.0537	50	1.84	1.86	1.88	-
6-330	8.19	0.491	0.1496	14.735	0.0540	38	3.20	2.96	2.72	10,750
6-345	7.13	0.491	0.1457	12.884	0.0557	25	7.63	7.63	7.77	14,300

Table 8.

REGRESSION LINES

for

FLEXURAL MODULUS OF ELASTICITY (psi*10^6)

versus

DYNAMIC MODULUS OF ELASTICITY (psi*10^6)

$MOE_f = a + b*E_d$

PANEL	a	b	r^2	r
1	0.406	0.924	0.9923	0.9916
2	-0.087	0.998	0.9701	0.9849
3	-0.116	0.947	0.9811	0.9905
4	-0.362	1.096	0.9881	0.9940
5	0.283	0.988	0.9794	0.9896
6	0.004	0.939	0.9970	0.9985
ALL	0.128	0.959	0.9816	0.9908

Table 9.

REGRESSION LINES

for

FLEXURAL MODULUS OF ELASTICITY (psi*10^6)

versus

RECIPROCAL OF STRESS WAVE TIME SQUARED (μ sec)^2

$MOE_f = a + b*(1/SWT^2)$

PANEL	a	b	r^2	r
1	0.435	4371	0.9918	0.9959
2	-0.132	4888	0.9685	0.9841
3	-0.110	4446	0.9828	0.9941
4	-0.326	5169	0.9857	0.9928
5	0.273	4807	0.9755	0.9877
6	0.029	4386	0.9957	0.9978
ALL	0.154	4545	0.9782	0.9890

Table 10.

REGRESSION LINES

for

TENSILE MODULUS OF ELASTICITY (psi*10^6)

versus

DYNAMIC MODULUS OF ELASTICITY (psi*10^6)

$MOE_t = a + b*E_d$

PANEL	a	b	r^2	r
1	0.282	0.887	0.9854	0.9927
2	-0.398	1.022	0.9647	0.9822
3	-0.203	0.974	0.9929	0.9964
4	-0.278	1.035	0.9638	0.9817
5	-0.169	0.985	0.9788	0.9893
6	-0.141	0.939	0.9876	0.9938
ALL	-0.063	0.955	0.9808	0.9904

Table 11.

REGRESSION LINES

for

TENSILE MODULUS OF ELASTICITY (psi*10^6)

versus

RECIPROCAL OF STRESS WAVE TIME SQUARED $(\mu sec)^2$

$MOE_t = a + b*(1/SWT^2)$

PANEL	a	b	r^2	r
1	0.304	4192	0.9857	0.9928
2	-0.450	5011	0.9657	0.9827
3	-0.195	4573	0.9931	0.9965
4	-0.246	4882	0.9621	0.9309
5	-0.181	4795	0.9742	0.9870
6	-0.115	4385	0.9864	0.9932
ALL	-0.039	4528	0.9781	0.9890

Table 12.

REGRESSION LINES
for
ULTIMATE TENSILE STRESS (psi)
versus
DYNAMIC MODULUS OF ELASTICITY ($psi*10^6$)

$MOR_t = a + b*E_d$

PANEL	a	b	r^2	r
2	2357	10180	0.8484	0.9211
4	4763	10034	0.8446	0.9190
ALL	3650	10089	0.8451	0.9193

Table 13.

REGRESSION LINES
for
ULTIMATE TENSILE STRESS (psi)
versus
DYNAMIC MODULUS OF ELASTICITY ($psi*10^6$)

$MOR_t = a + b*E_d + c*E_d^2$

PANEL	a	b	c	r^2	r
1	1853	-1294	746	0.9985	0.9992
3	9345	-4375	741	0.9776	0.9887
5	15395	-9521	1262	0.9580	0.9788
6	8679	-3993	758	0.9912	0.9956
ALL	10190	-5698	926	0.9521	0.9758

Table 14.

REGRESSION LINES

for

ULTIMATE TENSILE STRESS (psi)

versus

RECIPROCAL OF STRESS WAVE TIME SQUARED (μ sec)^2

$MOR_t = a + b*(1/SWT^2)$

PANEL	a	b	r^2	r
2	1644	$5.01*10^7$	0.8560	0.9252
4	4934	$4.75*10^7$	0.8487	0.9212
ALL	3332	$4.88*10^7$	0.8516	0.9228

Table 15.

REGRESSION LINES

for

ULTIMATE TENSILE STRESS (psi)

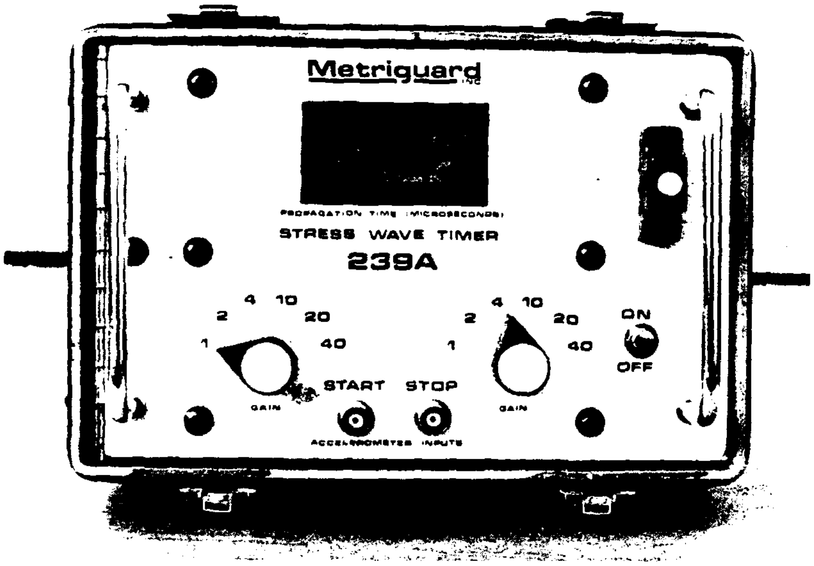
versus

RECIPROCAL OF STRESS WAVE TIME SQUARED (μsec)^2

$MOR_t = a + b*(1/SWT^2) + c*(1/SWT^2)^2$

PANEL	a	b	c	r^2	r
1	2006	$-0.65*10^7$	$1.68*10^{10}$	0.9997	0.9998
3	9296	$-2.05*10^7$	$1.64*10^{10}$	0.9758	0.9878
5	14960	$-4.56*10^7$	$2.98*10^{10}$	0.9408	0.9699
6	8365	$-1.77*10^7$	$1.63*10^{10}$	0.9943	0.9971
ALL	9017	$-2.39*10^7$	$1.99*10^{10}$	0.9345	0.9667

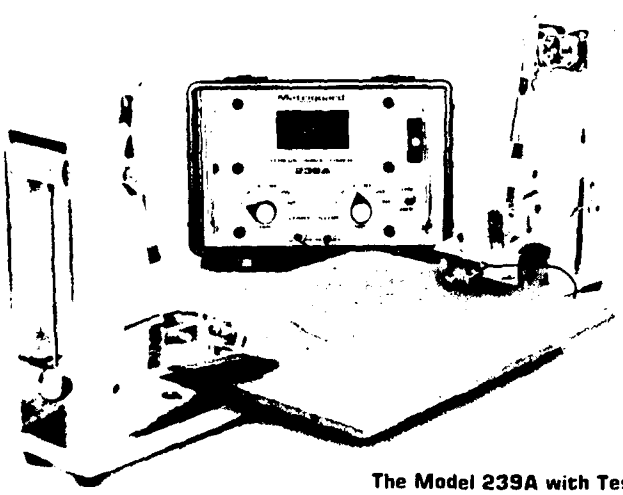
METRIGUARD Model 239A Stress Wave Timer



TYPICAL APPLICATIONS

- Portable field testing for rot in timbers
- Measurement of particle orientation
- Laboratory quality control programs
- Production line quality control
- Quality assurance programs for composite materials
- Sorting or grading according to material properties
- Quality control of incoming shipments
- Development of acceptable universal standards

- ☐ Lightweight and compact
- ☐ Tests nondestructively
- ☐ Can be set up in seconds
- ☐ Tests can be made by inexperienced personnel
- ☐ Digital readout gives instant indication of a board's quality



The Model 239A with Test Clamps

SPECIFICATIONS

Power Requirements: Nine volt battery (Eveready #522 alkaline cell or equivalent). A built-in regulator gives a low battery indication when the voltage drops below the value required for the regulator to function. Battery life in excess of 40 hours.

Resolution: ± 1 microsecond.

Controls: Individual front panel sensitivity switches and internal level controls for the "start" and "stop" channels.

Accelerometers: Ten-foot shielded cables with microdot connectors.

Portability: Remote operation without auxiliary power. Rugged carrying cases.

Weight: 20 lb., including clamps.

Dimensions: Instrument case — 7" x 9" x 9" high
Clamp carrying case — 8" x 11" x 11" high

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U.S. Army Materials Technology Laboratory,
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IN-PLANE STRESS WAVES FOR NDE OF GRAPHITE FIBER/EPOXY COMPOSITES-
Roy F. Pellerin

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Composite materials

Technical Report MTL TR 88-10, April 1988, 73 pp - illus-tables

Due to the complexity of the physical structure of composites, NDE techniques which evaluate structural properties are required rather than the mere detection of inclusions, voids or discontinuities. This paper describes NDE techniques that have been used for evaluation of properties in wood, a natural composite, and the results of utilizing longitudinal stress waves for evaluation of graphite fiber/epoxy composites. The objectives of this study were: 1) to become familiar with graphite fiber/epoxy composites; and 2) to establish if the NDE stress wave method, for wood, is appropriate for evaluation of the properties of composites, such as, graphite fiber/epoxy. One of the conclusions of this study was that graphite fiber/epoxy composites respond to stress wave analysis similar to the natural composite, wood. More specifically, the stress wave method of nondestructive evaluation of graphite fiber/epoxy composites can be used to accurately assess the strength and moduli properties within panels. Another conclusion was that the results of this study gave strong indication that every piece evaluation is both possible and feasible for quality control and process control purposes.

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Watertown, Massachusetts 02172-0001
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Due to the complexity of the physical structure of composites, NDE techniques which evaluate structural properties are required rather than the mere detection of inclusions, voids or discontinuities. This paper describes NDE techniques that have been used for evaluation of properties in wood, a natural composite, and the results of utilizing longitudinal stress waves for evaluation of graphite fiber/epoxy composites. The objectives of this study were: 1) to become familiar with graphite fiber/epoxy composites; and 2) to establish if the NDE stress wave method, for wood, is appropriate for evaluation of the properties of composites, such as, graphite fiber/epoxy. One of the conclusions of this study was that graphite fiber/epoxy composites respond to stress wave analysis similar to the natural composite, wood. More specifically, the stress wave method of nondestructive evaluation of graphite fiber/epoxy composites can be used to accurately assess the strength and moduli properties within panels. Another conclusion was that the results of this study gave strong indication that every piece evaluation is both possible and feasible for quality control and process control purposes.

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IN-PLANE STRESS WAVES FOR NDE OF GRAPHITE FIBER/EPOXY COMPOSITES-
Roy F. Pellerin

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Key Words

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